THE SPACE NUCLEAR REACTOR PROGRAM

HEARING

BEFORE THE

SUBCOMMITTEE ON
ENERGY RESEARCH AND PRODUCTION

AND THE

SUBCOMMITTEE ON
SPACE SCIENCE AND APPLICATIONS

OF THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

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THE SPACE NUCLEAR REACTOR PROGRAM

TUESDAY, MAY 24, 1983

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION,
SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS,
Washington, D.C.

The subcommittees met, pursuant to notice, at 1:30 p.m., in room 2325, Rayburn House Office Building, Hon. Marilyn Lloyd (chairperson of the Subcommittee on Energy Research and Production) presiding.

Present: Representatives Lloyd, Volkmer, Nelson, MacKay, Walker, and Lujan.

Staff present: John V. Dugan, Nelson Milder, Gordon Smith, William Harvey, and Joyce Gross Freiwald.

Mrs. LLOYD. The subcommittee will come to order. At this point I will ask unanimous consent that cameras and recording devices be allowed at the hearing today. Without objection.

Let me begin with a few words and then I'll turn to my good friend and colleague, Chairman Volkmer, for his introductory remarks.

The subject of our hearing today is of great importance to both our subcommittees, and I thank him for joining me in holding these proceedings.

On March 8 of this year, the Energy Research and Production Subcommittee held the first of what I indicated would be a series of hearings on the subject of space nuclear electric power research and development. At that point the subcommittee received testimony pursuant to the authorization of the Department of Energy's fiscal year 1984 budget request for this work. The information we received from the Department of Energy, from NASA, the Defense Advanced Research Projects Agency [DARPA] and the two principal laboratories responsible for managing the SP-100 project, clearly suggested that the decade-long pause in the U.S. space reactor R&D activities is coming to an end.

I for one am gratified by the resurgence of interest in this technology. From both civilian and defense perspectives, this Nation's space activities of the future will most certainly place greater demands upon the on-board electric power supply systems, both in the amount of power required and in the length of time the power supply systems must operate to meet more demanding mission objectives. For such missions, nuclear power appears to be the only viable approach.

Today we will continue our review of activities to be accomplished within the framework of the recent triagency agreement among DOE, NASA, and DARPA. In addition, we will receive a comprehensive review on the status of the U.S. technology base in space reactor systems research and development from the viewpoint of a NASA laboratory, two DOE laboratories, and the principal industry participants in the Department's recent technology assessment study.

It is only through a full understanding of the Nation's need for such power systems and an appreciation of our capabilities to develop safe, reliable, and compact space reactors for a wide range of electric power requirements that the members can adequately begin to address the policy issues that must be resolved in order to bring this technology to fruition.

Mr. Volkmer?

Mr. VOLKMER. Thank you, Madam Chairman.

I am pleased that we are holding this hearing on space nuclear power systems today. This is a subject that has been given a low priority for several years and one which now appears to be of considerable importance to the future of the civil space program.

The development of the shuttle space transportation system has established a new national resource for scientific, national security, and civil applications. It has opened the door to a new space era and challenges us to capitalize on our existing strengths. As space payloads increase in size and complexity, the harnessing of nuclear power for civil space applications could become a necessity if we are to meet that challenge. Already we can see the limits of our existing space power systems so now is an appropriate time to assess the issues related to the development of space nuclear reactors.

I am, therefore, looking forward to hearing testimony from our witnesses today who represent NASA, DOE, and industry. Their views on the status of the U.S. space nuclear power technology base will lay the groundwork for further analysis of the issues.

Thank you, Madam Chairman. I would like to mention one other thing. I will have to leave after a little while because I have a markup in another committee.

Mrs. LLOYD. We certainly understand. We have full schedules in all of our committee works.

Mr. Lujan?

Mr. LUJAN. Thank you, Madam Chairman, for this opportunity to welcome our witnesses. I'm glad to see that five of the eight people who will be testifying today are from the private sector. This representation from the private sector is very encouraging. By the same token, I notice we have no representatives from the Nation's colleges and universities. The technical support for these programs in future years will come from those institutions of higher learning which can train students through participation in the program now. Possibly we may be able to get more information on that aspect of the program either today or at a later time.

Another topic which should be explored today is the extent to which space nuclear reactors will be used in the future for civilian activities. I realize that the testimony discusses this to a limited extent but, again, possibly we can get more information on civilian

applications as we continue with this hearing. The continued support which the administration has provided for this program is encouraging to me and should be to the participants. As one of our witnesses has stated in the testimony, which I have read, the funding level is adequate as the program is presently defined. This early stage of program definition and development does warrant Federal support. I reiterate my interest for significant participation both by industry and universities in this important program. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Lujan.

Now we will proceed with our first witness, Mr. Henry Slone, who is Director, Space Technology Directorate, NASA-Lewis Research Center. We welcome you, Mr. Slone. We have your complete testimony. You may proceed as you wish because your entire statement will be made a part of the record.

STATEMENT OF HENRY O. SLONE, DIRECTOR, SPACE TECHNOLOGY DIRECTORATE, NASA-LEWIS RESEARCH CENTER, CLEVELAND, OHIO, ACCOMPANIED BY JEROME P. MULLIN, MANAGER, SPACE ENERGY SYSTEMS OFFICE, NASA/OAST, WASHINGTON, D.C.

Mr. SLONE. Thank you, Chairman Lloyd, Chairman Volkmer, and other members of the subcommittees.

I'm from the NASA-Lewis Research Center, Cleveland, Ohio, and I'm here to talk about Lewis's efforts in support of NASA's interest in the SP–100 program. We believe that the study of such a reactor energy source is important as part of the overall planning needed for a variety of high power civil, scientific, and military missions where the present solar array/battery systems are not competitive. These potential missions include deep space probes, orbits in intense radiation environment, long-term lunar and planetary bases, advanced space stations, and potential military missions.

As you know the use of nuclear reactors in space as a source for large quantities of energy has been pursued since the 1950's and Lewis Research Center [LeRC] has played a key role in these programs. Both nuclear electric power generation and nuclear rocket propulsion for manned lunar and planetary missions were investigated in these efforts. By 1973, however, the U.S. mission requirements changed and work aimed at a nuclear reactor power capability in space was essentially eliminated.

With the space shuttle now operational and a continuing demand by the civilian and military sectors of the Nation for increased power capabilities in their future missions, a fresh look at the application of nuclear energy in space is being conducted. The memorandum of agreement [MOA] signed on February 11, 1983, between the Defense Advanced Research Projects Agency [DARPA], the National Aeronautics and Space Administration [NASA], and the Department of Energy [DOE], established procedures whereby the three agencies will jointly develop the technology necessary for space nuclear reactor power systems for military and civil applications. The program office is located at DARPA Headquarters and consists of a DARPA program manager and NASA and DOE deputy program managers. A project office, located at NASA's Jet

Propulsion Laboratory [JPL], is responsible for the implementation of this program. The principal Government laboratories supporting this project office are the Los Alamos National Laboratory and Lewis Research Center.

Major elements of the present SP-100 program are safety, mission analysis and requirements, system definition, and nuclear and aerospace technology development. Lewis presently is now fully supporting the overall program in the mission analysis and requirements and systems definition elements and in the planning of the technology development element. Within the technology development element Lewis will be responsible for any future technology development efforts in its area of expertise in dynamic conversion systems and advanced conversion systems should the need arise in the program. Lewis is uniquely qualified to carry out these efforts based on our current capabilities in energy conversion systems development and analysis, and our previous efforts in support of nuclear reactor space power systems. Throughout the 1960's and 1970's Lewis successfully developed the technologies for the SNAP-8 dynamic Rankine space power system and the isotope Brayton space power system. I was the NASA project manager for both these projects. The Brayton space power system turbine-alternator-compressor unit was successfully tested for over 38,000 hours. The Brayton system including the rotating unit, heat exchangers, radiator, et cetera, completed over 3,000 hours of vacuum testing in the NASA space power facility. Lewis provided the overall systems engineering, assembly and test for the Brayton space power system.

In addition to this past experience on nuclear reactor space power systems Lewis has maintained a very active research program in many of the key technologies necessary for the successful development of space power systems. Major efforts are being carried out on photovoltaic energy conversion systems, power consolidation and control systems, fuel cells, advanced energy storage systems, development of advanced lightweight and more efficient components, waste heat management and advanced radiator concepts and determining the impact of the space plasma environment on the space power systems. Lewis has developed the insight and capability necessary to successfully integrate the individual components into overall space power systems.

I believe that Lewis is the national center of excellence for the development of space power systems and we have much to contribute to the present SP-100 program.

The Lewis SP-100 responsibilities include mission analysis and requirements and system definition. To carry out these responsibilities we set up an SP-100 project office with the personnel necessary to support this office. I will now very briefly describe and summarize our activities in the aforementioned areas.

In the mission analysis and requirements area our activities are focused on space station and space station derived missions. The purpose of our work is to identify potential NASA and commercial orbital missions that would require powers of the 100-kilowatt class or more and would materially benefit from the availability and unique characteristics of nuclear reactor space power systems. Nuclear reactor power systems applicability, utility and constraints for space station and space station derived applications will be

evaluated and documented. The power requirements and profiles for these missions will be identified as well as the potential impact of a nuclear reactor power system on the space station requirements. In addition, the nuclear reactor space power systems will be compared with alternative systems to identify regimes for the use of nuclear reactor power systems when appropriate. We will do this work through a combination of in-house activities and competitively procured contracted studies.

The next element is our systems definition element and in the first area we're looking at the shuttle/Centaur power system interface. The purpose of this effort is to establish an operating envelope for transferring nuclear reactor payloads to space via the shuttle and/or shuttle/Centaur and to provide specific design parameters and requirements for the system definition contracts to be let by JPL. This integration activity is being carried out so that any constraints that the shuttle/Centaur would require can be included in the design considerations and trades for the space power system. Specific areas of interest include structural attachment, separation techniques and mechanisms, electrical and control contracts, electromagnetic interference, cargo bay thermal conditioning, ambient temperatures, gas composition and vibroacoustics. It is also planned to address the safety issue of launching a spacecraft with a nuclear reactor power system in the shuttle/Centaur space vehicle, to define the malfunctions, anomalies, and abort modes which may occur, and to identify the resulting environments to which the power system and spacecraft will be subjected as a result of these occurrences. In this activity we will involve other NASA centers such as the Kennedy Space Center.

We are also evaluating test facilities for potential ground engineering systems tests, and in this coordinated project effort, we will identify and evaluate facilities that may be required. In assessing the need for ground engineering tests, the potential advantages of computer based systems modeling will be evaluated to determine if it is practical to eliminate part or all of the hardware for such tests. Lewis activities will initially focus on the identification of the overall potential of the NASA space power facility located at the Plum Brook Station for testing of such a ground engineering system, but other potential facilities will also be identified and assessed.

I might mention the NASA space power facility which was built in 1967, is the only facility in the Nation with combined nuclear and space vacuum capability, and was designed to assemble, test and disassemble a space reactor power system. Such tests of nuclear power systems have not as yet been conducted in the space power facility, hence it is not yet fully equipped. Thus, if it is required for the SP-100 program, SPF will have to be refurbished and properly equipped.

Turning to dynamic conversion systems, this is an area of Lewis expertise and we will provide that expertise to provide analytical and technical support to the SP-100 system definition team for candidate dynamic power conversion system design concepts such as Brayton, Rankine, and Stirling Cycles. We will also perform systems modeling and performance analysis to identify the overall potential of the candidate dynamic systems, assess the state of tech-

nology of the systems and identify any required technology development efforts.

Another area is systems evaluation and assessment wherein we will perform in-house analyses to comparatively evaluate alternative reactor space power systems and solar power systems for a range of mission requirements. This comparison will include reactor-thermoelectric system concepts, reactor-dynamic conversion systems, solar-dynamic conversion systems, solar photovoltaic power systems and thermophotovoltaic systems. The data developed in in-house tasks, in contracted studies, and in previously published studies will be used, together with any specific additional analysis required to extend or adapt these results, to provide consistent comparisons of the benefits and limitations of each system concept. Reference solar photovoltaic systems will be modeled from previous studies for comparison with the reactor systems. All systems will be compared on the basis of: performance, size, weight, area, STS compatibility. Sensitivity of these characteristics to power level, orbit, and to the way each system could be configured to meet mission requirements will also be assessed.

The results of these studies will provide a basis for determining whether it is more beneficial to use a nuclear reactor or an alternative space power system to provide power for specific applications. The studies will also allow a realistic comparison of the alternate approaches to be used in the development of nuclear reactor space power systems. Through these efforts, and incorporating the latest data on reactors from the Los Alamos National Laboratory, it is anticipated that Lewis can provide the systems analysis capability necessary to supply guidance to the SP–100 program throughout its entirety. Thus, the SP–100 project team will have an independent in-house capability to allow a continued reassessment of the attractiveness of the relative technologies as more information is received from the pertinent technology development projects.

We are also evaluating the potential improvements to the SP–100 reference design which would accrue from the replacement of the thermoelectric conversion subsystem and/or heat pipe radiator subsystem with subsystems based on advanced concepts, and we will recommend basic technology development efforts for attractive concepts.

Lastly, we're conducting a preliminary evaluation of space power systems in the 1- to 100-megawatt power range. The approach used to carry out this effort will be based on a combination of in-house analysis, competitively procured industry efforts and coordination and assessment of on-going relevant programs at other Federal laboratories and universities. This combined effort will result in a preliminary evaluation of the capabilities of advanced space nuclear reactor power systems in comparison with alternate chemical concepts, an estimate of the launch vehicle requirements for these systems, and preliminary conceptual designs of attractive concepts. The results will aid in identifying required technology development areas and supply the SP–100 project office with the justification and basis for proceeding with more detailed study, and technology development as appropriate.

Regarding the technology element of the effort, we are not currently engaged in technology development effort at the present

time. As the need is identified, however, Lewis will define and implement such efforts in the areas of advanced energy conversion systems and advanced components.

In summary, the Lewis Research Center continues to be the national center of excellence in space energy conversion systems. We have a heritage of past work in nuclear reactor space power dynamic conversion including the SNAP-8 and Brayton power systems. These efforts drew heavily on Lewis' expertise in the relevant technologies that have previously been invoked to support many power and propulsion projects for NASA, DOE, and DOD.

I am pleased to say that the SP-100 project activities at Lewis are on schedule and fully integrated with the JPL project office. Lewis is looking forward to contributing in a major way to this important national program.

Thank you for the opportunity to appear before you and present a review of our capabilities.

[The prepared statement of Mr. Slone follows:]

Statement
of
Henry O. Slone
Director, Space Technology Directorate
Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

before the

Subcommittee on Energy Research and Production
and
Subcommittee on Space Science and Applications
House of Representatives

Chairman Lloyd, Chairman Volkmer and Members of the Subcommittees:

My name is Henry Slone, Director of Space Technology at the NASA Lewis Research Center (LeRC). I am honored to appear before you today to present the LeRC efforts in support of the National Aeronautics and Space Administration's interest in the SP-100 space nuclear power program. We believe that the study of such reactor energy sources is important as a part of the overall planning need for a variety of high power civil, scientific, and military missions where the present solar array/battery systems are not competitive. These potential missions include deep space probes, orbits of intense radiation environment, long term lunar and planetary bases, advanced space stations, and potential military missions.

As you know the use of nuclear reactors in space as a source for large quantities of energy has been pursued since the 1950's and LeRC has played a key role in these programs. Both nuclear electric power generation and nuclear rocket propulsion for manned lunar and planetary missions were investigated in these efforts. By 1973, however, the U.S. mission requirements changed and work aimed at a nuclear reactor power capability in space was essentially eliminated.

With the Space Shuttle now operational and a continuing demand by the civilian and military sectors of the nation for increased power capabilities in their future missions, a fresh look at the application of nuclear energy in space is being conducted. The Memorandum of Agreement signed on February 11, 1983, between the Defense Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE), established procedures whereby the three agencies will jointly develop the technology necessary for space nuclear reactor power systems for military and civil applications. The program established by the agreement is entitled the SP-100 Program. The Program Office is located at DARPA Headquarters and consists of a DARPA Program Manager and NASA and DOE Deputy Program Managers. A Project Office, located at NASA's Jet Propulsion Laboratory (JPL), is responsible for the implementation of this Program. The principal government laboratories supporting this Project Office are the Los Alamos National Laboratory and LeRC.

Major elements of the present SP-100 Program are Safety, Mission Analysis and Requirements, System Definition, and Nuclear and Aerospace Technology Development. LeRC presently is now fully supporting the overall Program in the Mission Analysis and Requirements and Systems Definition elements and in the planning of the Technology Development element. Within the Technology Development element LeRC will be responsible for any future technology development efforts in its area of expertise in dynamic conversion systems and advanced conversion systems should the need arise in the Program. LeRC is uniquely qualified to carry out these efforts based on our current capabilities in energy conversion systems development and analysis, and our previous efforts in support of nuclear reactor space power systems. Throughout the 1960's and 70's LeRC successfully developed the technologies for the SNAP-8 dynamic Rankine Space Power System and the Isotope Brayton Space Power System. I was the NASA Project Manager for both these projects. The Brayton Space Power System turbine-alternator-compressor unit was successfully tested for over 38,000 nours. The Brayton System including the rotating unit, heat exchangers, radiator, etc. completed over 3000 hours of vacuum testing in the NASA Space Power Facility. LeRC provided the overall systems engineering, assembly and test for the Brayton Space Power System. The development of the major hardware items were accomplished on contract with industry. The Brayton Project drew heavily on LeRC expertise in power systems analysis, systems engineering, rotating equipment (especially turbines and compressors), heat transfer, materials, contract management, hardware assembly, and testing and evaluation.

In addition to this past experience on nuclear reactor space power systems LeRC has maintained very active research programs in many of the key technologies necessary for the successful development of space power systems. Major efforts are being carried out on photovoltaic energy conversion systems, power consolidation and control systems, fuel cells, advanced energy storage systems, development of advanced lightweight and more efficient components, waste heat management and advanced radiator concepts and determining the impact of the space plasma environment on the space power systems. LeRC has developed the insight and capability necessary to successfully integrate the individual components into overall space power systems.

Thus I feel that LeRC is the national center of excellence for the development of space power systems and that LeRC has much to contribute to the present SP-100 Program.

The LeRC SP-100 responsibilities include Mission Analysis and Requirements and System Definition. In the Mission Analysis and Requirements area, LeRC is responsible for space station and space station derived missions. In the System Definition area, LeRC is responsible for: definition of the Shuttle/Centaur-power system interface, evaluation of test facilities for Ground Engineering System tests, Dynamic Power Conversion Systems, Systems Analysis and Assessment, Advanced Thermal Conversion and Management Studies, and Multi-MWe System Concept Studies.

To carry out these responsibilities an SP-100 Office and the matrix support necessary to support this Office has been established at LeRC. I will now briefly describe the activities of the LeRC SP-100 Office in each of the above mentioned efforts.

MISSION ANALYSIS AND REQUIREMENTS

Space Station and Space Station Derived Missions

The LeRC activities are focused on studying space station and space station derived missions in support of the SP-100 Project mission requirements.

The purpose of this work is to identify potential NASA and commercial orbital missions that would require powers at the 100 KWe class or more and would materially benefit from the availability and unique characteristics of nuclear reactor space power systems. Nuclear reactor power systems applicability, utility and constraints for space station and space station derived applications will be evaluated and documented. The power requirements and profiles for these missions will be identified as well as the potential impact of a nuclear reactor power system on the space station requirements. In addition, the nuclear reactor space power systems will be compared with alternative systems to identify regimes where the use of nuclear reactor power systems is appropriate. This work will be accomplished through in-house and competitively procured contracted studies.

SYSTEMS DEFINITION

Definition of the Shuttle/Centaur Power System Interface

The purpose of this effort is to establish an operating envelope for transferring nuclear reactor payloads to space via Shuttle and/or Shuttle/Centaur and to provide specific design parameters and requirements for the System Definition Contracts to be let by JPL. This integration activity is being carried out so that any constraints that the Shuttle/Centaur would require can be included in the design considerations and trades for the space power system. Specific areas of interest include structural attachment, separation techniques and mechanisms, electrical and control contacts, electromagnetic interference, cargo bay thermal conditioning, ambient temperatures, gas compositions and vibroacoustics. It is also planned to address the safety issue of launching a spacecraft with a nuclear reactor power system in the Shuttle/Centaur space vehicle, to define the malfunctions, anomalies, and abort modes which may occur, and to identify the resulting environments to which the power system and spacecraft will be subjected as a result of these occurrences. We plan to involve the expertise of NASA Kennedy Space Center in addressing these launch related issues.

Evaluation of Test Facilities for Ground Engineering Systems Tests

In this coordinated project support effort, LeRC will identify and evaluate facilities that may be required for future tests of a nuclear reactor space power Ground Engineering System (GES). In assessing the need for Ground Engineering tests, the potential advantages of computer based systems modeling will be evaluated to determine if it is practical to eliminate part or all of the hardware for such tests. LeRC activities will initially focus on the identification of the overall potential of the NASA Space Power Facility (SPF) located at LeRC's Plum Brook Station for testing of such a Ground Engineering System, but other potential facilities will also be identified and assessed.
The NASA SPF, built in 1967, is the only facility in the nation with combined nuclear and space vacuum capability, and was designed to assemble, test and disassemble a space reactor power system. Such tests of nuclear power systems have not as yet been conducted in the SPF, hence it has not yet been fully equipped. Thus, if required for the SP-100 Program, SPF will have to be refurbished and properly equipped.

LeRC is re-examining the documentation on the SPF and defining the full potential of this unique facility for testing a nuclear reactor space power GES. The facility modifications that have been made in the past years will be examined and the present status of the facility will be determined. A plan (including cost and schedule) will be developed for refurbishment of the SPF to the condition necessary to meet the anticipated GES testing requirements. LeRC will identify where additional facility capability may be incorporated and/or refurbishment costs reduced in the light of new technological developments. The compatibility of the SPF for meeting any GES testing requirements will be evaluated in detail. In addition, LeRC will participate on a team which will identify and evaluate other facilities that may be used for future Ground Engineering tests if a need for such tests is identified.

Dynamic Conversion Systems

LeRC energy conversion expertise will be used to provide analytical and technical support to the SP-100 System Definition Team for candidate dynamic power conversion system design concepts such as Brayton, Rankine and Stirling Cycles. LeRC personnel have served as advisors in the evaluation of proposals for the JPL Concept Definition Contracts, and will aid JPL in the technical monitoring of the resulting contracts and serve on review teams to evaluate the contractor results. LeRC will also perform system modeling and performance analyses to identify the overall potential of the candidate dynamic systems, assess the state-of-technology of the systems and identify any required technology development efforts.

Systems Evaluation and Assessment

In addition to the above mentioned support to the SP-100 System Definition Team, LeRC personnel will perform in-house analyses to comparatively evaluate alternative reactor space power systems and solar power systems for a range of mission requirements. This comparison will include reactor-thermoelectric system concepts, reactor-dynamic conversion systems, solar-dynamic conversion systems, solar photovoltaic power systems and thermophotovoltaic systems. The data developed in in-house tasks, in contracted studies, and in previously published studies will be used, together with any specific additional analysis required to extend or adapt these results, to provide consistent comparisons of the benefits and limitations of each system concept. Reference solar photovoltaic systems will be modeled from previous studies for comparison with the reactor systems. All systems will be compared on the basis of: performance, size, weight, area, STS compatibility, etc. Sensitivity of these characteristics to power level, orbit, and to the way each system could be configured to meet mission requirements will also be assessed.

The results of these studies will provide a basis for determining whether it is more beneficial to use a nuclear reactor or an alternative space power system to provide power for specific applications. The studies will also allow a realistic comparison of the alternate approaches to be used in the development of nuclear reactor space power systems. Through these efforts, and incorporating the latest data on reactors from the Los Alamos National Laboratory, it is anticipated that LeRC can provide the systems analysis capability necessary to supply guidance to the SP-100 Program throughout its entirety. Thus, the SP-100 Project Team will have an independent in-house capability to allow a continued reassessment of the attractiveness of the relative technologies as more information is received from the pertinent technology development projects.

Advanced Thermal Conversion and Management Studies

LeRC will evaluate the potential improvements to the SP-100 Reference Design which would accrue from the replacement of the thermoelectric conversion subsystem and/or heat pipe radiator subsystem with subsystems based on advanced concepts, and will recommend basic technology development efforts for attractive concepts.

Because a wide range of advanced conversion (thermophotovoltaic, alkali metal thermal energy conversion, thermionic, etc.) and radiator (liquid droplet, belt, disk, etc.) subsystems are of interest, the evaluation will be conducted in two phases: (1) LeRC will perform an initial in-house screening to narrow the focus on those candidate concepts offering significant payoff and having a reasonable chance of success, and (2) LeRC will work with the SP-100 Project System Definition Team to perform a more detailed evaluation of the potential impact of these concepts on the overall nuclear reactor space power system capabilities. Technology development projects will be defined for attractive concepts and these will be implemented as the needs are identified.

Multi-MWe Systems Concepts

LeRC will conduct a preliminary evaluation of space power systems in the 1-100 MWe power range. The approach used to carry out this effort will be based on a combination of in-house analysis, competitively procured industry efforts and coordination and assessment of on-going relevant programs at other Federal laboratories and universities. This combined effort will result in a preliminary evaluation of the capabilities of advanced space nuclear reactor power systems in comparison with alternate chemical concepts, an estimate of the launch vehicle requirements for these systems, and preliminary conceptual designs of attractive concepts. These results will aid in identifying required technology development areas and supply the SP-100 Project Office with the justification and basis for proceeding with more detailed study, and technology development as appropriate.

TECHNOLOGY PROJECTS

Advanced Conversion and Technologies

LeRC is not yet engaged in any technology development efforts in direct support of the SP-100 Program. As the need is identified, LeRC will define and implement such efforts in the areas of advanced energy conversion systems and advanced components. It is anticipated that these needs will be identified in the efforts performed by the SP-100 System Definition Team, and by the work performed in the LeRC dynamic systems evaluation and assessment and advanced thermal conversion and management efforts.

SUMMARY

In summary, the Lewis Research Center continues to be the national center of excellence in space energy conversion systems. LeRC has a heritage of past work in nuclear reactor space power dynamic conversion including the SNAP-8 and Brayton Power Systems. These efforts drew heavily on LeRC expertise in the relevant technologies that have previously been invoked to support many power and propulsion projects for NASA, DOE, and DOD.

I am pleased to say that the SP-100 Project activities at LeRC are on schedule and fully integrated with the JPL Project Office. LeRC is looking forward to contributing in a major way to this important national program.

Thank you for the opportunity to appear before you and present a review of our capabilities.

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Mrs. LLOYD. Thank you, Mr. Slone.

Mr. Volkmer, since you'll have to be leaving pretty soon I would like for you to proceed with your questions at this time. I appreciate your being with us this afternoon.

Mr. VOLKMER. Thank you.

Can you tell me what NASA missions have been previously identified for space nuclear reactors and what are their power requirements, if any?

Mr. SLONE. Well, at the present time we are in the process of identifying civil missions. For example, we're looking at space stations as a potential application, but there are also other potential missions such as planetary missions that would require nuclear reactors.

Mr. VOLKMER. In regard to a space station. If we're looking to use a nuclear reactor, what would be the timetable for having a reactor ready to go for a station?

Mr. SLONE. I would say in the midnineties.

Mr. VOLKMER. In the midnineties?

Mr. SLONE. Yes.

Mr. VOLKMER. In other words, if we were to use this as an energy source for a space station we wouldn't be able to use it until 1995 or thereafter?

Mr. SLONE. Probably; the initial space station will probably have a solar power system.

Mr. VOLKMER. Well, it would have to, assuming what you're telling me then.

Mr. SLONE. Yes.

Mr. VOLKMER. Now, in the testing that will take place for the nuclear power reactors, will you use the facility at Plum Brook?

Mr. SLONE. Well, we're presently investigating the use of the facility at Plum Brook, but we're also looking at other possible facilities.

First, we have to establish the need for a ground engineering system test and we're doing that.

Mr. VOLKMER. We're not to the point yet where we know whether we will have to use Plum Brook or not?

Mr. SLONE. That is correct.

Mr. VOLKMER. All right.

When will we have some idea?

Mr. SLONE. Hopefully within the year we will have results.

Mr. VOLKMER. Within this fiscal year or within this calendar year?

Mr. SLONE. I was just reminded we probably will not have complete answers until 1985.

Mr. VOLKMER. Until 1985?

Mr. SLONE. Yes.

Mr. VOLKMER. Whether or not you'll need to use the facility at Plum Brook?

Mr. SLONE. Correct.

Mr. VOLKMER. And that's presently under lease, is it not?

Mr. SLONE. Yes, it is under lease to the Garrett Corp.

Mr. VOLKMER. And if it's used it will have to be refurbished?

Mr. SLONE. That is correct. It would have to be refurbished.

Mr. VOLKMER. So sometime, probably next year, you would have to make a decision whether or not you are going to request any funds for refurbishment of it or are you going to wait until 1985 and ask for 1986?

Mr. SLONE. It would probably wait until the 1985 time period to request funds.

Mr. VOLKMER. It would be fiscal year 1986 then when you apply for funds, if you're going to use it?

Mr. SLONE. Yes.

Mr. VOLKMER. What is the most complex technical area in dealing with and designing a nuclear reactor for space?

Mr. SLONE. I would say that safety is our No. 1 predominant activity in all areas.

Mr. VOLKMER. Safety from radiation?

Mr. SLONE. Safety from all aspects.

Mr. VOLKMER. All right.

Is there any difficulty that you can foresee in the compactness of it?

Mr. SLONE. Well, we have to worry about the compactness of it from the standpoint of launch capability. That's one of the activities that we're looking at now.

Mr. VOLKMER. What about the weight?

Mr. SLONE. Weight and volume both.

Mr. VOLKMER. Who is responsible for these areas, the safety areas?

Mr. SLONE. That comes out of the project office at JPL, but there are independent safety groups that are, if you will, tied to both the project office and the steering committee. We do have quite an activity underway in safety, and JPL is leading that activity.

Mr. VOLKMER. And who would be responsible for design as far as compactness, volume, and density.

Mr. SLONE. The DOE is responsible for the heat source—the reactor—and we at NASA would then be responsible for all other technologies such as power conversion, power processing and so forth, as well as system integration, and we would be working together for the complete design.

Mr. VOLKMER. All right.

Do you have any opinion at the present time whether or not we will be able to use the shuttle bay for a spacecraft with a 100-kilowatt power reactor?

Mr. SLONE. No, sir, that's one of the areas that we are evaluating at the present time.

Mr. VOLKMER. So, you don't have any opinion at this time?

Mr. SLONE. I do not.

Mr. VOLKMER. But are you of the opinion that eventually, if we go to a larger space station for manufacturing pharmaceuticals or crystals or whatever processes, we will need a nuclear-type reactor?

Mr. SLONE. It is my opinion that we will. I think the power requirements will be such that we will need a nuclear source.

Mr. VOLKMER. And what would be the length of time that you are looking to provide power for. Power source for years, hours, or what?

Mr. SLONE. Years.

Mr. VOLKMER. The last question is, What's going to happen to it when it's no longer useful?

Mr. SLONE. Well, that's one of the safety considerations that we're looking at. That's a very important consideration.

Mr. VOLKMER. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Volkmer. Thank you, Mr. Slone for your very excellent testimony. We're happy to have you with us and we're certainly going to be counting on your expertise and knowledge in this very vital program.

You were very much involved in the SNAP program, as you testified. We're all very interested in technology transfer. What do you think are the key lessons that we can learn from that work and how applicable is this to our present and future programs in our space nuclear power systems program?

Mr. SLONE. Well, I think we do have a technology base that we can draw on. If you remember we were doing work over quite a few years and a lot of that work is still available to us in terms of the technologies and I believe it can be easily transferred among the groups now involved.

Mrs. LLOYD. It is my understanding that this work is primarily addressed to the power systems in the 100-kilowatt range. Do you think we need to be working on larger systems for our civilian applications?

Mr. SLONE. We do have a study which we call the multimegawatt study in which we're looking at ranges of 1 to 100 megawatts. I think that we should absolutely do that.

Mrs. LLOYD. Do you think that our funding level is adequate to take us to 1986?

Mr. SLONE. I believe our funding level is adequate to go to the 1985 decision.

Mrs. LLOYD. I'm very much interested in the civilian missions. How far are we along in NASA's program for developing a real need for a nuclear electric power system, and what is it going to take to complete this?

Mr. SLONE. Well, right at the present time, as I mentioned earlier, we're actively looking at the space station-type of mission and we are studying other missions, but I don't really have any answers for you regarding that at the moment.

Mrs. LLOYD. I'm very concerned that your space power facility which is now presently under arrangement with the Garrett Corp. Since the centrifuge manufacturing they are doing is also of interest to this subcommittee, what arrangements can we make with Garrett should SPF be needed for the SP-100 program?

We also have Mr. Mullin with us from NASA Headquarters. Thank you for being with us today.

Mr. SLONE. I was just reminded we're still in the process of negotiating with the Garrett Corp. on their use of SPF and alternatives are being suggested if we do have to get into SPF, but I don't have any final answer.

Mrs. LLOYD. Tell us about the Lewis in-house capability and some of the technology developments such as materials, components, structures. Is this capability being applied to the SP-100 program?

Mr. SLONE. Yes; it is. We're utilizing all of our resources now within the areas that we're working on. At the present time I have

assigned seven full-time professionals plus what I refer to as matrix support, and we have about 12 man-years of effort devoted to the SP-100 where we're drawing on our expertise in materials, controls, dynamics, et cetera. I believe that we do have the resources and expertise available to carry out this program.

Mrs. LLOYD. That's certainly good to know.

Tell us a little bit about our present technology base. Is it really adequate? Could we provide a space power system for some near-term defense mission, say within the next 3 to 5 years? Is that too broad a question?

Mr. SLONE. I think it's too broad a question. I think it would depend on the mission and things of that nature. I don't believe I can answer that right at the moment.

Mrs. LLOYD. Do you think that our technology development should precede our mission definition and planning, or should these efforts be parallel?

Mr. SLONE. Well, they are going on in parallel and I believe that's the way it should be right at the moment.

Mrs. LLOYD. Thank you very much for being with us, Mr. Slone. I think Mr. Lujan has some questions for you now.

Mr. LUJAN. Thank you, Madam Chairman.

Mr. Slone, does that mean that we're going to have different sizes of reactors? Are we looking for one for space station-type use, one for space exploratory missions, and a different size for defense requirements? Is that what we're looking at?

Mr. SLONE. No; that's not necessarily the direction we're going in. There's a possibility that there could be different size reactors; yes.

Mr. LUJAN. Are we talking about a compact little reactor, or a reactor the size of about 100 megawatts—what we would envision——

Mr. SLONE. It will be compact and it will be about a meter in diameter. It won't be very large, what we're thinking of right at the moment.

Mr. LUJAN. Do we have any kind of an idea what the power needs are for a space station?

Mr. SLONE. At the present time in space station we're right in the midst of defining what those power needs are and we're talking about power needs to the user, so to speak, on space station of 30 to 50 kilowatts at the moment, but there is no space station design.

Mr. LUJAN. But you anticipate that that's the size of the reactor?

Mr. SLONE. It's in that range; yes.

Mr. LUJAN. What size was SNAP-10?

Mr. SLONE. SNAP-10 was 500 watts. That was a reactor-thermoelectric conversion system.

Mr. LUJAN. Oh, 500 watts?

Mr. SLONE. Yes.

Mr. LUJAN. That is pretty small. One of the things that concerns me in all our programs, usually, is the reinvention of the wheel. Why isn't it possible since DOE has the expertise in nuclear reactors—I get the feeling that it's something new to NASA——

Mr. SLONE. No; it isn't new to NASA.

Mr. LUJAN. How many reactors has NASA developed?

Mr. SLONE. Oh, I'm sorry. NASA does not develop reactors. I misunderstood.

Mr. LUJAN. Why don't you just go to DOE and say we need such and such a size reactor in this particular size, much like the military does?

Mr. SLONE. Well, this is a joint program with the DOE because it is vital that the reactor is integrated into the entire system from the beginning.

Mr. LUJAN. But you're talking about moving the engineering and all of that over to Plum Brook.

Mr. SLONE. No.

Mr. LUJAN. What are you going to do there?

Mr. SLONE. The Plum Brook facility would be used if there's a ground engineering system test that's required. The DOE would be involved in that also.

Mr. LUJAN. You mean to test a ground system?

Mr. SLONE. To test a system on the ground.

Mr. LUJAN. Don't the national laboratories under DOE already have those capabilities?

Mr. SLONE. We are looking at those facilities, also. As I stated, we're looking at the space power facility which is a vacuum facility and has a nuclear capability, but we're looking at the facilities at the national labs.

Mr. LUJAN. What's going to make that determination; who has the best facilities?

Mr. SLONE. First of all, the determination will be made do we indeed need such a test, and the extent of such a test. Then it will be based on the best facility capability available.

Mr. LUJAN. Would an engineering test work?

Mr. SLONE. To some degree. It's not so much does it work, I think we believe it will work, I think it would be more in terms of performance and reliability and lifetime.

Mr. LUJAN. So that when you say if such a facility is needed, it's almost a foregone conclusion that such a facility will be needed for testing. You can't just say here's the concept, we're going to put it together. We'll put it in the Shuttle and send it up.

Mr. SLONE. No; you could test the individual subsystems. You could test the heat source by itself, the reactor, and you could test the conversion system by itself—without putting them together.

Mr. LUJAN. We wouldn't do that, would we?

Mr. SLONE. We might do that.

Mr. LUJAN. Put a whole reactor system in space having just tested the components and not having tested the system.

Mr. SLONE. This is done. It's done with rocket systems. You never quite get the complete system together.

Mr. LUJAN. That's a little surprising to me but I don't know very much about building reactors nor things like that.

In reading over some of the other testimony, the private sector, specifically Rockwell and GA Technologies, say they have the people to do it. They can reassemble those teams very easily. Why not do that?

Mr. SLONE. We are using the private sector. We are using the industry via contracts. This is a combined——

Mr. LUJAN. For component parts?

Mr. SLONE. Yes. We will use the industry, absolutely, and the universities.

Mr. LUJAN. I forgot to ask that. I put it in my opening statement and didn't ask the question.

Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Lujan. I would like to welcome the ranking minority member of our committee, Mr. Walker. We would like to recognize you at this time for any opening statement you might have to make and any questions.

Mr. WALKER. Thank you, Madam Chairman. I would just submit an opening statement for the record, if I might.

Mrs. LLOYD. Without objection it will be made a part of the record.

[The prepared statement of Mr. Walker follows:]

STATEMENT BY THE HONORABLE ROBERT S. WALKER

SPACE NUCLEAR REACTOR PROGRAM HEARING

MAY 24, 1983

THANK YOU MADAM CHAIRMAN. YOU ARE TO BE COMMENDED FOR SPONSORING THE HEARING TODAY ON SPACE NUCLEAR REACTOR PROGRAM.

AS I HAVE SAID EARLIER, THIS HEARING IS OF IMPORTANCE SINCE OUR ENTIRE COMMERCIAL FUTURE IN SPACE IS VERY CLOSELY ALIGNED WITH OUR ABILITY TO DEVELOP A SAFE AND RELIABLE NUCLEAR POWER SOURCE. IT IS MY BELIEF THAT ONCE WE ARE ABLE TO PROVIDE SUFFICIENT ELECTRIC POWER ABOARD SPACE CRAFT, BOTH MANNED AND UNMANNED, OUR FRONTIERS BECOME ALMOST UNLIMITED. I AM CERTAINLY INTERESTED IN THIS TESTIMONY ABOUT A PROGRAM WHICH ADDRESSES THE 100 KILOWATT LEVEL NOW AND CONSIDERS A COURSE OF ACTION WHICH WILL TAKE US TO A MULTI-MEGAWATT CAPABILITY IN THE FUTURE. I HAVE TOTAL ASSURANCE THAT THE APPLICATIONS FOR THIS PROGRAM WILL BE FOUND BOTH IN SPACE AND ON LAND-BASED PROJECTS.

MADAM CHAIRMAN IT IS ENCOURAGING TO HEAR THAT THE LAPSE IN THE SPACE NUCLEAR REACTOR PROGRAM HAS NOT SERIOUSLY JEOPARDIZED THE DATA BASE WHICH WAS ESTABLISHED EARLIER AND THAT MANPOWER IS AVAILABLE TO CONTINUE TO PICK THE PROGRAM UP FROM YEARS PAST. THIS ABILITY INDICATES TO ME THAT IT IS POSSIBLE TO CARRY MANY PROGRAMS FORWARD, PLACING THEM IN STORAGE WHEN ECONOMIC CONDITIONS OR TECHNICAL DATA SO INDICATE, AND REVIVING THEM AT A LATER DATE WHEN MOTIVATED BY OUTSIDE CONDITIONS.

AGAIN, MADAM CHAIRMAN, YOUR LEADERSHIP IN THE SPACE NUCLEAR REACTOR PROGRAM IS APPRECIATED.

Mr. WALKER. Just a couple of questions.

Why, when we're taking a look at space station capabilities, are we deciding now to go with nuclear reactors rather than sticking with the solar capability that has, up till now, characterized most of our electrical applications in outer space?

Mr. SLONE. I'm sorry, I was misunderstood. We are not deciding to go with nuclear reactors. We're looking at the use of nuclear reactors in the space station.

Mr. WALKER. Let me just change the question then a bit. Why are we moving in the direction of looking at nuclear when we have already seen some applications of solar. Why not upgrade the applications of solar capabilities rather than spend the money putting a nuclear program into place?

Mr. SLONE. Well, we absolutely are looking at solar capability for the space station, but as the power requirements go up, the solar arrays become larger and larger and larger, and that presents problems to us in terms of their usefulness in space. I don't know what that limitation is for solar arrays, that is where they are not suitable, but that's what we're looking at. There is some power level at which solar arrays may just not be attractive.

Mr. WALKER. The thing that puzzles me a little bit about that is that here some months ago, and I guess it is still to some extent an operating philosophy, we heard a lot about solar power satellites and they would be able to generate considerable megawattage. There was some question about the expense of moving in that direction but there was never really very much of a question about the technology itself, and we would not have the problems with the technology in terms of transmitting the power to Earth that are generally the leading problems with solar power satellites. I'm wondering why the divergence there. Why are we concerned about the arrays in outer space when that didn't seem to be a problem when we were talking about solar power satellite?

Mr. SLONE. The problem is that space station will be in low Earth orbit, and as the solar array becomes larger you have drag on the system. Then we also have to worry about batteries and this presents what we call a resupply problem. So these are just considerations that we have to take into account. Nothing is settled yet. There is no space station design.

Mr. WALKER. How similar is the planning for this kind of reactor to the reactors now used for military purposes and submarines?

Mr. SLONE. I believe there is quite a difference between the two situations.

Mr. WALKER. Is there an SP--100 reference design and, if so, can you give us some idea of its main design features?

Mr. SLONE. There is a reference SP-100 design. That's what we refer to as a reactor thermoelectric system. It's a reactor heat pipe, heat source the Los Alamos National Lab has been doing this work. The Jet Propulsion Lab has been doing the work on the thermoelectric conversion system.

Mr. WALKER. Is there any understanding at this point as to when such a system could be made operational?

Mr. SLONE. You mean a reference system?

Mr. WALKER. A reference system.

Mr. SLONE. We're really looking at the technical feasibility of that reference system right now. I can't really give an answer.

Mr. WALKER. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Walker.

Would you elaborate a little more on the Plum Brook facility, give us a little description of what kind of facility we're talking about?

Mr. SLONE. The Plum Brook facility is a large vacuum chamber. It's about 100 feet in diameter and about 60 feet high, if you can visualize that. It's a very large facility. It was built for both the vacuum capability and what we refer to as the nuclear capability. There are assembly and disassembly areas but unfortunately, or fortunately, however you want to look at it, it was never used in that capacity.

Mrs. LLOYD. But you say this facility has unique characteristics?

Mr. SLONE. Yes, very unique. Unique in the Nation.

Mrs. LLOYD. Back to the solar power systems, wouldn't that be a little bit expensive to try to plan on this technology to reach the goal of 100 kW or larger power systems?

Mr. SLONE. On what technology?

Mrs. LLOYD. On the solar electric system—to reach these power levels?

Mr. SLONE. No; I think we have come a long way with photovoltaics and solar array systems, but there is some power level that it just won't be too attractive for missions.

Mrs. LLOYD. Thank you, Mr. Slone.

Mr. MacKay, I believe, is with us.

Mr. MACKAY. I don't have any questions.

Mrs. LLOYD. Thank you for being with us and we hope to see you back here very soon.

Mr. SLONE. Thank you.

Mrs. LLOYD. Thank you, also, Mr. Mullin.

Our next witness is Dr. William O. Harms. He is the Director of Nuclear Reactor Technology Programs at Oak Ridge National Laboratory. We're very happy to have him with us today. He comes from the Third District of Tennessee, so I'm very happy to have him here as well.

We're also happy to have Dr. James R. Powell, Reactor Systems Office, Brookhaven National Laboratory.

Gentlemen, we have your prepared statement. It will be made part of the record. You may summarize or proceed as you wish in presenting your testimony.

STATEMENT BY DR. WILLIAM O. HARMS, DIRECTOR, NUCLEAR REACTOR TECHNOLOGY PROGRAMS, OAK RIDGE NATIONAL LABORATORY

Dr. HARMS. Thank you, Madam Chairman. I would like to reciprocate with warm greetings from your many loyal constituents in and around Oak Ridge.

Mrs. LLOYD. Thank you very much.

Dr. HARMS. Madam Chairman and members of the subcommittees, I am very pleased to have the opportunity to speak to you today on the subject of the U.S. technology base for the develop-

ment and deployment of space nuclear power reactor systems. In this presentation, it is my intent to provide some useful insights on this important subject and to cite several technology areas that I consider to be key to the success of the current triagency SP-100 program.

By way of background, the institution I represent—the Oak Ridge National Laboratory—has extensive and varied experience and capability in the space nuclear-power field, as described in some detail in my written statement. Pertinent to the subject of this hearing are our involvement during the 1960's and early 1970's as a major participant in a number of important space fission reactor programs and our participation earlier this year in a comprehensive space nuclear reactor design studies program sponsored by the Department of Energy.

The earlier efforts at ORNL were in connection with the systems for nuclear auxiliary power [SNAP] programs designated SNAP-8, SNAP-10, and SNAP-50; the NASA advanced lithium-cooled space power reactor; and the medium power reactor experiment [MPRE] project in which the conceptual design and total systems development of a unique direct cycle concept were carried out at ORNL. All of these systems, I should point out, involve liquid alkali metals as coolant or working fluid.

The recent DOE-sponsored space reactor design studies addressed both near term and longer term applications, as does the current SP-100 program. By way of brief summary, the ORNL team selected two basic concepts, each of which features conventional liquid metal fast breeder reactor-type fuel-pin core design and an alkali metal coolant or working fluid. The version recommended for nearest term application is one for which the LMFBR technology is directly applicable. For this version, a ground test demonstration program could be completed by 1990, which is consistent with the current SP-100 program near-term schedule. The schedules for the advanced ORNL versions lag that for the initial version by about 3 years.

The near-term goal of the SP-100 program is to deploy a space reactor system of the 100 kilowatt-electric class in the early- to mid-1990's. Accordingly, the near-term schedule calls for a concept decision and the beginning of a ground demonstration program in about 2 years. Midterm objectives include improved versions of the 100-kilowatt class; for the long term, multimegawatt concepts are under consideration.

As regards these three program phases, the U.S. base technology effort should represent an appropriate balance within whatever boundary conditions are imposed. The near-term phase is of primary importance because development tasks that could impact the mid-1985 concept decision must be identified soon and initiated without delay.

The technology areas that in my view merit attention on a priority basis in the current technology assessment and advancement phase of our national program are set into the framework that I have just described. These areas, in which ORNL has a recognized high level of expertise, are advanced materials, Rankine cycle technology, radiation shielding, controls, and measurements, and core design support. Detailed discussions of each of these areas are in-

cluded in the written statement. I shall briefly discuss here only the first two because, as I perceive the present priorities, schedule, and funding commitments, these areas have the highest potential for impacting the decisionmaking process during the important near-term phase of the SP–100 program. Another reason is that, according to present indications, ORNL will play a lead role in advanced materials technology and an important support role in Rankine cycle technology in this program.

First, then, the advanced materials technology area.

Discussions concerning requirements for advanced materials in space reactor systems normally center on a class of materials known as refractory or heat-resistant alloys. The reason for this is that the high performance levels desired for these systems require very high operating temperatures that are well in excess of those for which more conventional alloys, such as the stainless steels, can be used.

It is instructive to graphically relate system performance and materials requirements. First, for reference purposes, this chart shows the relationship between specific energy—a useful measure of system performance—and reactor outlet temperature. It is the trend indicated in this plot and not the numerical values of specific energy that is significant. The systems included here range from the relatively low-power, short-lived early SNAP systems to the later relatively high-performance devices shown in the upper right portion of the figure. If, as is generally conceded, the absolute upper limit for the use of stainless steels is about 1,470° F., it is apparent from this plot why the refractory alloys must be considered if the desired high-performance levels are to be achieved.

The approximate temperature limits for application of these alloys from the standpoint of strength alone are indicated in the next chart in the form of an overlay of the first chart. Shown here are the stainless steels, the superalloys, and the refractory alloys based on niobium, molybdenum, tantalum, and tungsten, in order of increasing refractoriness. For reference purposes, the white heat range begins at about 2,400° F.

In addition to strength, candidate alloys must meet other requirements such as compatibility with fuel materials, coolants, and working fluids; weldability; ductility; and resistance to irradiation damage. Certain of these alloys may be unacceptable in regard to one or several of these requirements. Take the superalloys, for example. It has been indicated that the cobalt- or nickel-based superalloys could fill the temperature gap, so to speak, between the stainless steels and the refractory alloys as shown in this chart. However, there are many uncertainties regarding these alloys that will require extensive investigation before firm decisions to use them can be made. Among the principal concerns are the embrittling aging reactions that are known to occur in these metallurgically complicated alloys. Moreover, the superalloys, like the stainless steels, do not offer the possibility for achieving the required high-performance levels. These considerations strongly suggest that advanced materials developed for the SP–100 program should be concentrated on the refractory alloys.

For concepts requiring materials decisions today, only a system based on stainless-steel-clad uranium oxide fuel and stainless steel

structural materials operating at around 1,200° F.—LMFBR conditions—can be considered technology ready. This situation stems from the existence of the broad and comprehensive engineering data base generated in LMFBR programs worldwide over the past 30 years and from the relative shortage of engineering data and experience with the refractory alloys. A measure of the relative abundance of data on stainless steel as compared to refractory alloys is shown in the next chart, where numbers of citations in the information data base at the DOE Technical Information Center are compared.

I wish to emphasize that the issue regarding the use of refractory alloys applies to the near term only. There is no question that for midterm and long-term considerations refractory alloys will dominate the space nuclear reactor systems materials picture. Indeed, the risks associated with using refractory alloys, even near the limits of their potential, could be significantly reduced in about 3 years. Now, a stated purpose of the prioritization process for the SP-100 program near term is to aim for the lowest risk concept meeting minimum requirements while promoting future growth. The basic question, therefore, is whether, for the near term, to go with the relatively low-performance parameters and marginal growth potential—from the materials standpoint—associated with the low-risk stainless steels or to proceed with a refractory alloy at a substantially higher risk—even with certain tradeoffs or compromises, such as shorter reactor life and less than optimum operating temperatures. A clearer assessment of this problem should be possible in several months when the minimum systems requirements will have been defined.

I will now discuss the Rankine cycle technology area.

A strong candidate for the power conversion subsystem is known as the Rankine cycle, which was employed in the SNAP-8, SNAP-50, MPRE, and NASA advanced space reactor programs. The Rankine cycle is used for conversion of heat to electricity in today's nuclear and fossil steam powerplants where the working fluid is water.

For high-temperature space systems, the working fluid is an alkali metal such as potassium. For the space power applications under consideration, Rankine cycle systems compete with Brayton cycle systems, in which the working fluid is a noncondensing gas. A major advantage of the Rankine cycle is its low specific weight and its substantially smaller radiator, by factors of 5 to 10, for a given power level.

For the early midterm, a promising concept that minimizes many performance concerns is a liquid lithium-cooled reactor transferring heat to a potassium Rankine cycle in a once-through boiler with heat rejection to space through a heat pipe radiator. A direct boiling reactor and power conversion system such as that developed in the MPRE project offers sufficient advantages to justify its consideration for the later midterm. However, some important development work remains to be done to advance potassium Rankine-cycle technology to a state where definitive system designs can be developed.

Special attention must be given to the control of liquid-vapor interfaces under the orbital flight conditions of microgravity—essen-

tially zero gravity. The problem may be described as follows: The design and operation of two-phase liquid-vapor systems at or near the Earth's surface is relatively simple because, under the force of gravity, the heavier liquid phase tends to go down while the lighter vapor phase tends to go or stay up. However, in the near-zero gravity of outer space, these phases must be managed or controlled through special engineering designs that make use of nongravitational forces to do the job. These include surface tension forces—tapered condenser tubes—or centrifugal forces—special twisted tape or wire-coil inserts in boiler tubes. It should be clearly understood that the problem here is not one of feasibility but of technological development and demonstration, much of which has already been done.

A program for developing the needed technology for both of the Rankine-cycle concepts I have described is outlined in the written statement. Many of the tasks can be carried out under Earth-surface gravity conditions. Ultimately, however, the evaluation of designs for controlling two-phase fluid behavior will require experiments performed in the space shuttle. This important aspect of the program crosscuts all of the other activities, and schedules and funding must accommodate this need.

This concludes my prepared remarks. I trust that some of them will prove useful, and I thank you for the opportunity to discuss these matters.

[The prepared statement of Dr. Harms follows:]

TESTIMONY

**PRESENTED TO THE SUBCOMMITTEES ON
ENERGY RESEARCH AND PRODUCTION
AND
SPACE SCIENCE AND APPLICATIONS
OF THE
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES**

May 24, 1983
Washington, D.C.

WILLIAM O. HARMS

Director, Nuclear Reactor
Technology Programs

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OAK RIDGE NATIONAL LABORATORY
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STATEMENT OF

WILLIAM O. HARMS
DIRECTOR, NUCLEAR REACTOR TECHNOLOGY PROGRAMS
OAK RIDGE NATIONAL LABORATORY

BEFORE THE SUBCOMMITTEES ON

ENERGY RESEARCH AND PRODUCTION
AND
SPACE SCIENCE AND APPLICATIONS

COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

May 24, 1983

Madam Chairman, Mr. Chairman, and Members of the Subcommittees, I wish to thank you for the invitation to speak to you today on the subject of the U.S. technology base for the development and deployment of space nuclear power reactor systems. In this testimony, it is my intent to provide some insights on this important subject and to cite several key technology needs that have been identified by staff of the Oak Ridge National Laboratory (ORNL). By way of background, I will first briefly review the experience and capabilities at ORNL in the field of space nuclear systems, and then summarize the results of a recent ORNL space reactor studies effort.

The Oak Ridge National Laboratory has extensive and varied experience and capability in space nuclear power research and development. For radioisotope heat source applications, we have developed and produced isotopic fuel forms and cladding alloys over the past decade or so. Currently we are producing iridium alloy fuel-cladding material and carbon-bonded carbon-fiber insulating sleeves for the Radioisotope Thermoelectric Generator (RTG) General Purpose Heat Source Program; both of these materials were developed at the Laboratory for this joint Department of Energy (DOE) and National Aeronautics and Space Administration (NASA) program.

During the 1960s and early 1970s, ORNL was a major participant in a number of space fission reactor programs. These included the Systems for Nuclear Auxiliary Power (SNAP) programs designated SNAP-8, SNAP-10, and SNAP-50; the NASA Advanced Lithium-Cooled Space Power Reactor; and the ORNL Medium Power Reactor Experiment (MPRE) project that involved

the conceptual design and total systems development of a direct Rankine cycle nuclear power concept.

The principal areas of involvement by ORNL in these programs were fuel development, development and characterization of advanced structural alloys and cladding alloys, design comparisons of candidate liquid-metal systems and working fluids, shielding analyses and experiments, development of controls and measurements techniques, and construction and operation of refractory alloy and stainless steel systems for liquid-lithium and boiling-potassium pumped-loop corrosion experiments. Integrated space power system mockups were also built and operated. More recently, ORNL has assisted the Los Alamos National Laboratory (LANL) in the fabrication and characterization of molybdenum alloy heat pipes for the in-core heat pipe space reactor concept. The Oak Ridge National Laboratory currently has a cadre of experts representing all the disciplines associated with nuclear reactor projects: design, physics, shielding, fuels, materials, high-temperature structural design methods, safety, heat transfer, controls and instrumentation, and systems and components development.

Earlier this year, ORNL participated in a space nuclear reactor studies program sponsored by DOE. The results of the ORNL studies appear in ORNL/CF-83/25, Space Nuclear Power Systems Reactor Studies — Phase I Report, February 14, 1983. I shall briefly summarize the results of these ORNL studies at this time because of their relevance to the overall consideration of technology needs in the SP-100 Program for both the short and the long term.

RECENT ORNL SPACE REACTOR SYSTEMS STUDIES

The task statement for the recent DOE-sponsored space reactor study in which ORNL participated called for power levels ranging from 250 to 8000 kilowatts thermal (kWt) and a steady-state power capability of seven years. Two fast-spectrum reactor concepts were selected by the ORNL study team: (1) the liquid metal cooled fuel pin reactor concept, adaptable to any of the several static and dynamic power conversion options, in three versions; and (2) the direct-Rankine-cycle boiling liquid metal cooled fuel pin concept, in two versions. The results of the study were reported in terms of the key reactor subsystem

features and parameters, the development requirements through ground demonstration testing and component flight qualification, and key safety objectives and issues.

Liquid Metal Cooled Fuel Pin Reactor

The liquid metal cooled fuel pin reactor concept is supported by a strong engineering and technology base, having been extensively developed during the 1960s and early 1970s in the SNAP-2, -8, -10A, and -50 programs and in the NASA Advanced Lithium-Cooled Space Power Reactor Program.

The generic features of this concept include (1) conventional fuel pin core design, (2) metal-clad ceramic fuel pins, (3) liquid metal coolant under forced circulation, (4) reflector control, (5) orderly growth potential from an initial state-of-the-art version to advanced high-performance versions, and (6) adaptability to a variety of power conversion systems.

For the initial or "nearest-term-application" version of this concept, the reactor outlet temperature is 650°C (1200°F), the fuel is conventional stainless-steel-clad uranium oxide (UO_2), the structural alloy is stainless steel, and the coolant is potassium. The liquid metal fast breeder reactor (LMFBR) technology that has been developed and demonstrated over the past 30 years for temperatures to 650°C (1200°F) is directly applicable to this version. Accordingly, it is essentially a state-of-the-art version, and ground testing, including posttest examination, could reasonably be completed by 1990.

It was assumed that for the nearest-term application this subsystem would be coupled to a state-of-the-art thermoelectric power conversion subsystem through cesium heat pipes. Power levels above 1500 kWt were not included, because in a conservative first design the number of heat pipes for such levels would be unmanageably large.

For improved versions of this concept, reactor outlet temperatures of 1150°C (2100°F) and 1260°C (2300°F) were selected. Based on data available from earlier efforts on space reactor development, uranium nitride (UN) fuel clad with a tantalum base alloy, a tantalum base alloy

structural material, and lithium coolant were selected for these versions. The cladding and structural alloys selected for the improved versions are T-111 (Ta-8W-2Hf) and ASTAR 811C (Ta-8W-1Re-0.7Hf-0.025C), respectively. Because additional fuel and materials development, including extensive irradiation testing, will be required for these advanced versions, ground testing of the reactor subsystem probably will be delayed by at least three years relative to that for the initial version. If these improved versions are to be considered for coupling to Rankine cycle power conversion subsystems, two-phase, near-zero-gravity testing also becomes a critical development need.

Boiling Liquid Metal Cooled Fuel Pin Reactor

A boiling liquid metal cooled fuel pin reactor of the type developed in the Medium Power Reactor Experiment (MPRE) program at ORNL was selected as the second concept for this study. In this concept, the reactor subsystem serves in a single circuit as the power supply for direct conversion in a Rankine cycle. Such a direct Rankine cycle system is attractive because it is relatively simple in comparison with two-circuit systems and because it affords the best potential for low system mass and size for a given power level.

The generic features of this concept include (1) conventional fuel pin core design, (2) metal-clad ceramic fuel pins, (3) boiling potassium as the working fluid, (4) reflector control, and (5) potential growth from an initial near state-of-the-art medium-power version to advanced higher-power, higher-performance versions.

The initial version is characterized by its moderate reactor outlet temperature of 760°C (1400°F), LMFBR-type stainless-steel-clad UO_2 fuel pins, and stainless steel structural material. The basic design adopted is that developed for the MPRE, for which the reactor outlet temperature was 840°C (1540°F) and the specified lifetime was 10,000 h (1.14 years). In view of the requirement for a seven-year lifetime, the operating temperature for the initial version was lowered relative to that for the MPRE. The results of integrated-Rankine-cycle system endurance tests performed in the MPRE program are directly

applicable to this version. Some additional irradiation testing of the fuel system at 760°C (1400°F) will be required. The single critical technology identified is that directed at managing two-phase fluid behavior under conditions of essentially zero gravity.

The reactor outlet temperature for the improved version of this concept is 1090°C (2000°F), and the fuel system and structural material proposed are the same as those recommended for the first improved version of the first concept, namely UN clad with T-111 alloy as fuel and T-111 alloy as structural material. In addition to the critical technology needed for investigating two-phase fluid behavior in space, there is the requirement for advanced fuel and structural alloy development for this version. In view of the critical technology requirements cited, the project schedules for the second ORNL concept lag behind those for the first concept by about three years.

Safety Plan

A preliminary safety plan was developed for both concepts. This plan is in line with the U.S. nuclear safety policy and criteria for space nuclear fission reactors as set forth in DOE Order OSNP-1. It includes a comprehensive fault tree analysis and addresses the principal safety objectives and critical environments of the reactor life cycle phases: ground handling and transportation, prelaunch and launch, ascent, and orbit. A safety strategy and logic network leading to preparation of the required safety analysis reports were also developed. The major safety issues have to do with maintaining subcriticality and preventing physical damage during these phases. Methods for resolving these issues include the use of sealed shipping containers; fixed subcriticality devices; positive lockout devices to disable reactivity-control mechanisms; and devices for ejecting the shield, reflector, and containment to promote atmospheric burnup on reentry.

SOME KEY BASE TECHNOLOGY AREAS

In the light of this background information, I shall now discuss some of the base technology areas that in my view merit attention on a

priority basis in the current technology assessment and advancement phase of our national program. For the near term, deployment of a space nuclear reactor power system of the 100 kilowatt-electric (kWe) class in the early-to-mid 1990s has been considered. The schedule associated with this undertaking calls for a concept decision and the beginning of a ground demonstration program in about two years. Mid-term requirements would include improved versions of the 100-kWe class as well as perhaps initial concepts for the low-multimegawatt class. Higher-multimegawatt concepts would be slated for the long term.

As regards these three program phases, the U.S. space nuclear reactor base technology effort should represent an appropriate balance within whatever boundary conditions are imposed. The near-term phase would appear to be of primary importance because research and development tasks that could impact the 1985 concept-decision point associated with this phase must be identified soon and initiated without delay. In addition, however, important generic work applicable to candidate systems in all program phases should be identified and implemented as soon as possible, and the options that might reasonably develop as the near-term process unfolds should be thoroughly examined and evaluated.

The key base technology areas I shall now discuss briefly are cast into this framework.

Advanced Materials Technology

Discussions concerning requirements for structural and fuel-cladding alloys in space reactor systems normally center on a class of materials known as refractory alloys. The reason for this is that the high performance levels desired for these systems (i.e., high powers, high heat-to-electricity conversion efficiencies, and low mass and size) require very high operating temperatures and, therefore, materials that retain high strength and other key properties at temperatures well in excess of those for which more conventional alloys, such as the stainless steels and the super alloys, can be used. An approximate but useful measure of

refractoriness is the melting point of the metal upon which a system of alloys is based — iron (mp 1535°C) for stainless steels, for example. (The temperature limit for useful application of an alloy from the standpoint of strength is in the range of 50 to 60 percent of its absolute melting temperature.) The refractory alloys under consideration for space nuclear systems applications are those based on niobium (mp 2415°C), molybdenum (mp 2620°C), tantalum (mp 2996°C), and tungsten (mp 3410°C).

The relationship between specific energy (a useful performance figure of merit) and reactor outlet temperature for a number of space power systems is presented in Fig. 1. If, as is generally conceded, the absolute upper limit for the use of stainless steels is about 800°C (1470°F), it is apparent from this plot why the refractory alloys must be considered if the desired high-performance levels are to be achieved. The relative elevated-temperature strengths of stainless steel, the super alloys, and the refractory alloys are shown in Fig. 2 in terms of the stress required to produce 1% strain or deformation in 10,000 h. The approximate temperature limits for application of these alloys from the standpoint of strength alone are indicated in the overlay of Fig. 1 shown in Fig. 3.

In addition to the strength criteria just cited, candidate alloys for these high-temperature applications must meet other requirements as well. These requirements include (1) compatibility with fuel materials and with reactor coolants and working fluids, (2) availability in the product forms required (e.g., piping, tubing, forgings for pumps and other components, sheet, and plate) on a time scale that is consistent with the project schedule, (3) weldability, (4) ductility, (5) acceptable friction and wear properties, and (6) resistance to irradiation damage. Based on the current state of the technology, certain refractory alloy systems may be unacceptable in regard to one or several of these additional requirements. For example, the low ductility and poor weldability of tungsten and molybdenum alloys rather preclude their being regarded at this time as candidate structural alloys, which must be capable of withstanding multiaxial, variable strain-rate loads in the accepted sense of load-bearing structural materials.

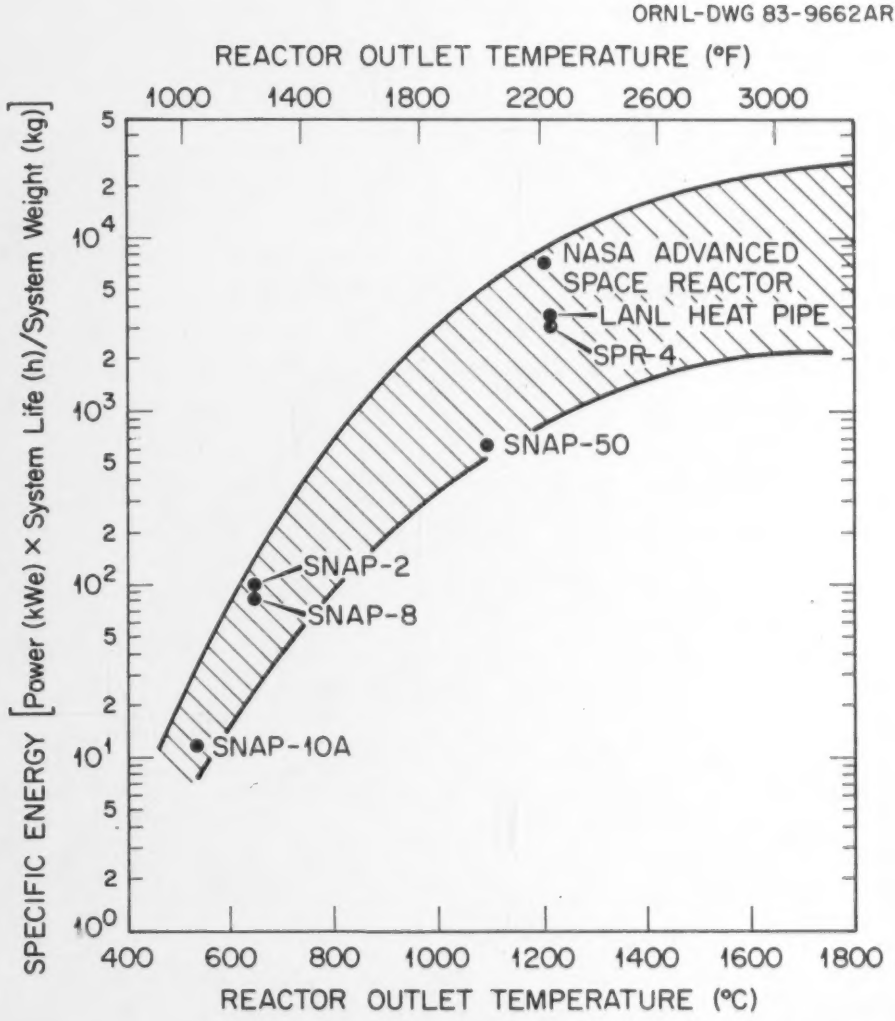

Fig. 1. Relation between specific energy and reactor outlet temperature for a number of space power systems showing that the high performance levels desired for space nuclear reactor systems will require high operating temperatures.

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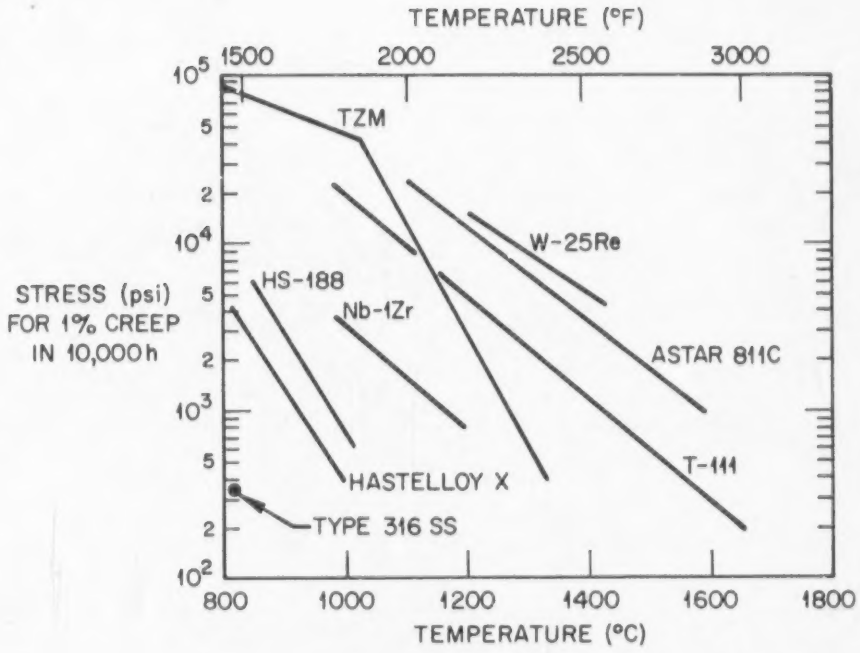

Fig. 2. Relative high-temperature strengths of stainless steel (Type 316 SS); super alloys based on nickel (Hastelloy X) and cobalt (HS-188); and refractory alloys based on niobium (Nb-1Zr), molybdenum (TZM), tantalum (T-111 and ASTAR 811C), and tungsten (W-25Re).

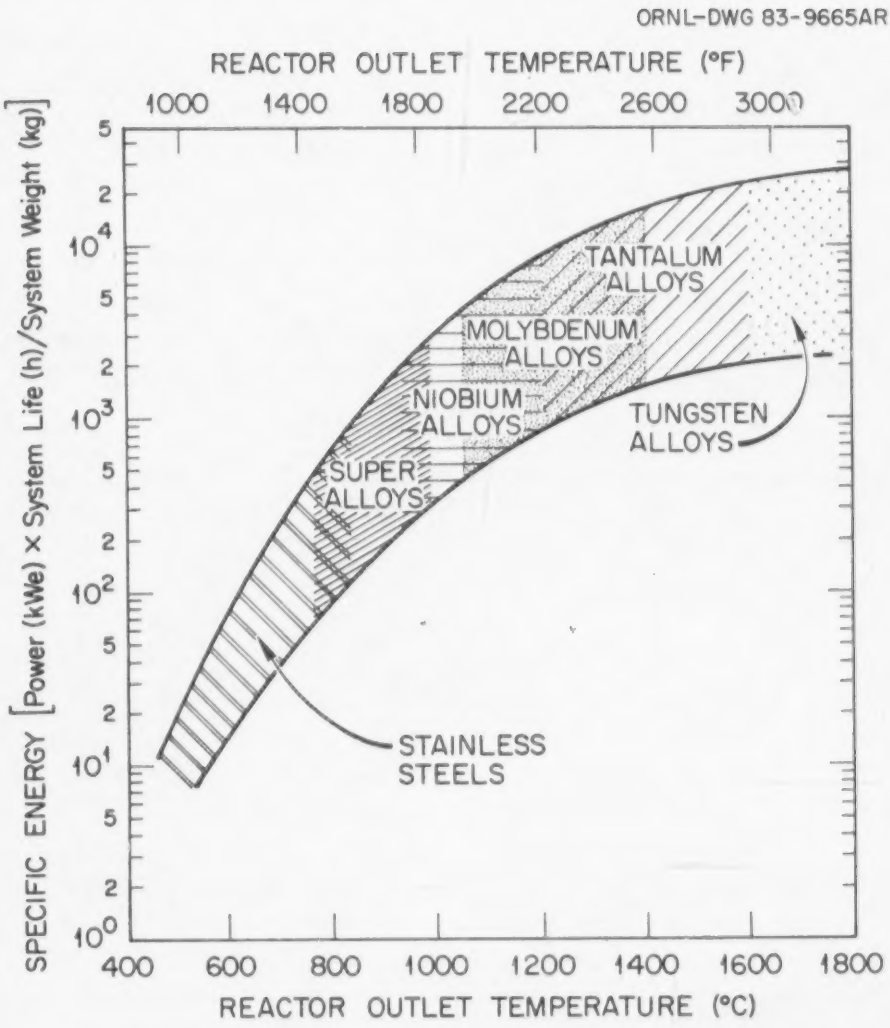

Fig. 3. Overlay for Fig. 1 indicating approximate temperature limits of application, from the standpoint of strength, for stainless steels, super alloys, and refractory alloys.

Only a system based on stainless-steel-clad UO_2 as fuel and stainless steel structural materials operating at around 650°C (1200°C) is considered to be fully qualified and "technology ready" for concepts requiring materials decisions today. This situation stems primarily from the existence of the broad and comprehensive fuel technology and engineering data base generated in LMFBR development and demonstration programs worldwide and from the relative paucity of engineering data and experience with the super alloys and the refractory alloys. A measure of the relative abundance of data on stainless steel as compared to refractory alloys is shown in Fig. 4, where numbers of citations in the information data base at the DOE Technical Information Center are compared.

Whether the operational temperature limit for stainless steel/UO_2 systems can be extended to 750°C (1380°F) or possibly 800°C (1470°F) must await further assessment. In any case, the very low strengths of the stainless steels at these temperatures would have to be dealt with in design, and appropriate fuel irradiation tests would have to be performed and evaluated on a priority basis for the purpose of near-term decision making.

The nickel-base alloy Hastelloy X (20-23Cr, 8-11Mo, 17-20Fe, 2Co, 1W) and the cobalt-base alloy HS-188 (20-24Cr, 20-24Ni, 13-16W, 3Fe) included in the high-temperature-strength plot shown in Fig. 2 are typical super alloys that could be considered for application in space nuclear power systems. It has been indicated that the super alloys could fill the temperature gap, so to speak, between the stainless steels and the refractory alloys as shown in Fig. 3. However, there are many uncertainties regarding these alloys — principally with respect to their long-term metallurgical stability under the proposed operating conditions — that will require careful investigation before firm decisions to use them can be made. Among the instability concerns are (1) the loss of important relatively high-vapor-pressure alloying elements such as chromium in the high vacuums of outer space and (2) embrittling aging reactions that are known to occur in these relatively complicated

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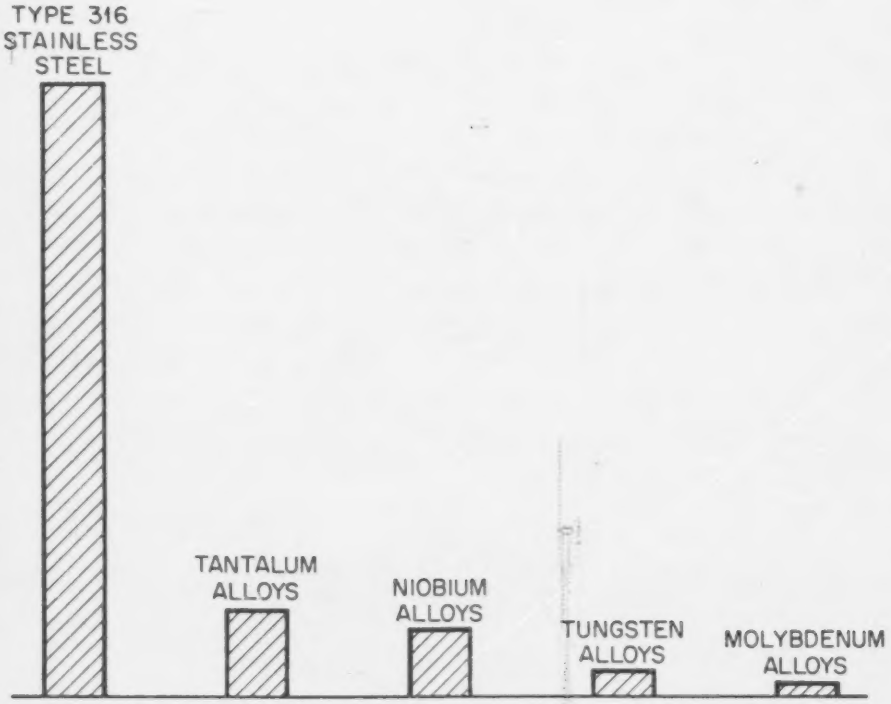

Fig. 4. Comparison of the number of citations for refractory alloys relative to type 316 stainless steel in the DOE information data base.

multiphase alloys. Moreover the super alloys, like the stainless steels, offer only limited growth potential. These considerations suggest that research and development on advanced materials for the SP-100 Program should be concentrated on the refractory alloys.

It should be emphasized that the issue regarding the use of refractory alloys applies to the near term only. There is no question that for mid- and long-term considerations refractory alloys will dominate the space nuclear reactor systems materials picture. Once the needed research and development work is started, the risks associated with using refractory alloys, even near the limits of their potential, could be significantly reduced in about three years. The question is whether in the short term to go with the low performance parameters and "dead end" of little or no growth potential (from the materials standpoint) associated with the low-risk stainless steel system, or to proceed with a refractory alloy — even with certain tradeoffs or compromises, such as shorter reactor life and less-than-optimum temperatures — at a substantially higher risk.

Among the major problems associated with the refractory metal systems as structural alloys is the unavailability of the product forms needed for engineering system and component testing programs. The refractory alloy industry virtually collapsed after the demise of the space nuclear systems program in the mid 1970s, and it has been estimated that from one to one and one-half years would be required to restore the capability needed. Other problems are related to the lack of adequate engineering data bases and information concerning weldability and the effects of irradiation.

To assist in the near-term decision making process and in focussing on just what additional refractory alloy development tasks are needed, ORNL, in conjunction with the DOE Oak Ridge Operations Office, has organized a workshop and symposium on refractory alloy technology to be held in mid August of this year. The participants will include experts who were active in the field during the 1960s and early 1970s. These experts, with the assistance of selected advisory committees, will present position papers covering the state of the technology and the development needs for all of the refractory alloy systems and technology

areas mentioned earlier (compatibility, fabrication, mechanical properties, etc.). The information from this symposium will be made available to all SP-100 Program participants in the form of published proceedings.

Rankine Cycle Technology

A strong candidate for the power conversion subsystem in a space nuclear system is one based on what is known as the Rankine cycle. The conversion of heat to electricity in today's power plants is based on the Rankine cycle where, in this case, water is converted to steam to drive the turbine-generator equipment, the steam is subsequently condensed, and the cycle is repeated. For high-temperature space systems, essentially the same process occurs, but the working fluid is an alkali metal such as potassium. Rankine cycle power conversion was employed in the SNAP-8, SNAP-50, MPRE, and NASA Advanced Lithium-Cooled Reactor Space Power Reactor programs of the 1960s and early 1970s. For the high-power, high-conversion efficiency space power applications, Rankine cycle systems compete with Brayton cycle systems, in which the working fluid is noncondensing gas.

A promising concept for the early midterm that minimizes many performance concerns is a liquid lithium-cooled reactor transferring heat to a potassium Rankine cycle in a once-through boiler with heat rejection to space through a heat pipe radiator. However, much development work remains to be done to advance potassium Rankine-cycle technology to a state where definitive system designs can be developed. Special attention must be given to the control of liquid-vapor interfaces, fluid transport, and fluid inventory location — as well as achieving adequate liquid-vapor separation — under the orbital flight conditions of microgravity (essentially zero gravity).

The single-loop system or direct boiling reactor, such as the MPRE and the second concept studied recently by ORNL, eliminates the intermediate heat exchanger, thereby reducing weight, and offers sufficient advantages in operational performance and reliability to justify its consideration as a backup to the two-loop concept.

A program directed at solving problems for both concepts should include the following component-performance oriented activities:

1. For the once-through boiler subsystem of the two-loop system: Demonstrate boiling of the working fluid to essentially dry vapor while achieving adequate resistance to thermal cycling of the heat exchanger tube walls; control mass transfer so as to minimize degradation in heat transfer or increase in pressure drop; achieve complete evaporation and some superheat at boiler discharge or develop techniques to separate residual liquid mist from the discharge stream prior to turbine entry.
2. For the radiator subsystem of both sytems: Adapt existing heat pipe technology to requirements of Rankine cycle heat rejection; develop surface-tension-driven mechanisms for returning condensate to the boiler under zero-gravity conditions; examine alternative heat rejection concepts.
3. For the turbine-generator/turbine-pump subsystems of both systems: Prove the performance of potassium-driven turbine generators and pumps based on previous designs and tests at ORNL and at three industrial contractor organizations; develop and demonstrate appropriate bearings and seals for service in potassium liquid and vapor environments.
4. For the direct boiler subsystem of the single-loop system: Improve delineation of heat extraction limits (critical heat flux) in fuel pin bundles; characterize boiling stability associated with liquid superheat (temperature oscillations) and channel flow (pressure drop); demonstrate resistance of the cladding to thermal cycling fatigue; establish adequacy of core cooling and effects of flow distribution hardware.
5. For the separator subsystem of the single-loop system: Develop a liquid-vapor separator as an integral element of the direct boiler; develop recirculation devices for returning separated liquid to the core inlet.

6. For the integrated systems: Establish performance under transient conditions that occur during startup/shutdown and acceleration/deceleration; demonstrate long-term performance, control, and lifetime in appropriate ground-based facilities.

Much of the activity in these major developmental tasks can be carried out under earth-surface gravity conditions. Ultimately, however, the evaluation of two-phase fluid behavior during orbital flight will require experiments performed under conditions of microgravity. Prior studies in this area have been limited to short-period exposures using drop towers and aircraft trajectories. Current capabilities, such as ballistic rockets and the space shuttle, can provide the long-duration exposures required to test and develop components and subsystems. This important aspect of the program crosscuts all of the other activities described, and schedules and funding must accommodate this need.

In the early stages of this program, design optimization studies will be performed using cold flow models and out-of-reactor boiling-potassium loop tests. Scaled experiments will then be devised for studying steam-water flows and, later, boiling-potassium flows in a microgravity environment. Initially, aircraft trajectory and/or drop-tower tests will be performed. The results of these tests used in combination with cold flow models should provide an adequate basis for the design and construction of test modules for space shuttle experiments.

Module tests will be carried out in the space shuttle using an electrically heated boiler and other components — such as pumps, separators, mixers, and recirculators — developed in the earlier phases of the program. Phase separation, liquid recirculation, liquid inventory, and thermal mixing will be monitored in these tests. Subsequently, integrated systems tests in scaled equipment would be needed for monitoring the responses to transients and off-design conditions.

A necessary supporting element in this program is the development of instrumentation and data acquisition systems for obtaining the desired test data — primarily temperature, flow, and power measurements — under both ground-based and orbital-flight circumstances. The

substantial existing data base on space flight instrumentation should serve as a springboard for this effort.

Radiation Shielding Technology

All space power reactor systems must include a radiation shield to protect the payload, the components of the system itself, and crews (for manned missions) or maintenance personnel. The choice of shield materials and the design optimization with respect to weight and shape are important and may be crucial. For protection of the electronics, the shield must ensure that limits on the radiation level per unit time as well as the integral exposure dose are not exceeded.

Shield materials must be selected for their radiation attenuation characteristics, for their stability under the operating temperature and radiation environments, and for their stability under launch and accident conditions. Idealized shield designs are always compromised by penetrations required for coolant flow and control devices; these penetrations provide streaming paths and complicate the design and fabrication. Therefore, the final shield design must be based on a detailed shield analysis, which in turn must be based on a sound reactor shielding technology.

By way of background, lithium hydride is most often mentioned as the primary neutron shield material for space power reactor systems. Indeed, lithium hydride does provide the greatest neutron attenuation per unit weight of any candidate neutron shield material. However, the design and fabrication experience for lithium hydride shields is based on reactor systems with lower power levels and much simpler designs than those now being considered. The SNAP-10A flight system, for example, contained a lithium hydride shield in the shape of a cone frustrum with no penetrations. Casting of lithium hydride shields is very difficult, especially for nonsymmetrical shapes and for shapes containing penetrations. After casting, the lithium hydride is very brittle and has very low thermal conductivity. Thermal conductivity is particularly important in multimegawatt systems because shield system temperatures will be above the melting point of lithium hydride. The construction of

reliable containers for molten shield materials would impose severe weight penalties and further complicate the shield design. (Lead was rejected as a gamma ray shield in SNAP systems in the 1960s because of the difficulties anticipated in dealing with a molten shield in space.)

Alternative materials that have not received significant study include hydrides other than lithium hydride and materials containing boron. Although alternative materials probably will be heavier than lithium hydride for a given attenuation, other properties may make them attractive, particularly in multimegawatt power systems where shield weight may not dominate system weight.

For gamma-ray shielding, tungsten and depleted uranium are often mentioned as candidate materials. Lead, although attractive because of its low secondary gamma-ray production rate, is usually eliminated because of its low melting point. Uranium is not recommended for use near the reactor core because possible fissioning in the uranium would result in additional heat generation and possible swelling in the shield.

In view of these considerations, a generic shielding program should be conducted to (a) evaluate potential shielding materials in terms of radiation attenuation effectiveness as a function of weight and size and (b) identify optimum arrangements of neutron and gamma-ray shield materials in a laminated design (i.e., for minimum thickness or weight). Experimental verification of the most desirable shield configurations should be performed followed by an analytical and experimental study of shield penetration effects for characterization of realistic shield designs.

Resources needed to perform the required analyses have been developed at ORNL for previous shielding programs, most notably the NASA SNAP program, the Department of Defense weapons effects program, and the DOE fast breeder reactor programs. Experimental verification of shield designs is possible using either the ORNL Tower Shielding Facility (TSF) reactor or a modified SNAP 10-A reactor with a SNAP 2 shield assembly available at the TSF. These resources could form the basis upon which

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to build the capabilities that will be required for the design and verification of space reactor shielding. However, virtually all of them will require updating and modernization.

Controls and Measurements Technology

Comprehensive controls and measurement systems that are beyond the state of the art will be required if the current high-performance goals set for space nuclear systems are to be met. Accordingly, a generic base technology effort, including the development of high-performance (heat and radiation resistant) components such as control actuators, neutron detectors, and temperature sensors applicable to all concepts, should be established early in the reactor development process.

For a given reactor concept, a reactivity control system with adequate shutdown margin and safety under all postulated conditions must be developed to reliably control power during the lifetime of the reactor. Appropriate control regimes, including performance specifications and criteria, must be developed to meet the long-term stability requirements for power generation and load-following capability.

The scope of this work would be as follows:

- Develop components such as control actuators, neutron detectors, and temperature sensors that are beyond the state of the art for space reactor applications.
- Develop and evaluate performance specifications and criteria associated with such key space reactor power systems problems as
  - the methodology for unattended startup from a cold and clean condition to full power on command from a timing signal;
  - the need for start and restart from various initial conditions and for stable control under anticipated or unanticipated load changes;
  - means for assuring continued operation with limited failures such as a stuck control drum, nonuniform burnup, or unanticipated component failure; and
  - the ability of the coupled system — core, heat transport loop, power conversion subsystem, heat rejection subsystem,

and instrumentation and controls — to undergo transients with adequate margins with respect to limiting conditions (i.e., conditions that could cause plant shutdown or even component failure).

- Provide an independent evaluation of the adequacy of the proposed measurements and controls systems to meet mission requirements.

Core Design Support Technology

Neutronics benchmarks will be needed by space nuclear reactor core designers for biasing or adjusting nuclear data used in verifying criticality safety margins, establishing control worth requirements, determining power distributions, and assessing neutronic spectral effects. A neutronic benchmark consists of a complete description of a previously performed critical experiment, which is representative of a core design concept under consideration, along with an updated neutronics analysis. It provides a common base for the comparison of core neutronics analytical capabilities.

The purpose of this recommended work is to develop and continuously update a sourcebook on neutronics benchmarks for use as reference quality assurance standards in the design of space reactor concepts. This program could be very cost effective by eliminating the need for some critical experiments, which, as compared to those performed in the 1960s, will be both more expensive and time consuming as a consequence of (a) more stringent safety requirements and (b) the very limited number of facilities available today for space reactor critical experiments.

The scope of the effort would include developing and documenting existing data from a large number of space reactor critical experiments. Much of the information from these experiments is generic in terms of refractory structural alloys, fuels, coolants, and core and reflector geometries. These benchmarks would be updated as data from new experiments become available, and confirmatory analytical support would be provided to SP-100 design teams as required.

This concludes my prepared statement. Thank you again for the opportunity to discuss these matters with you.

Biographical Information

WILLIAM O. HARMS

Dr. William O. Harms is Director of Nuclear Reactor Technology Programs at the Oak Ridge National Laboratory (ORNL). He is responsible for the Breeder Reactor Program, the Space Nuclear Systems Program, the Light Water Reactor Technology Program, and the Nuclear Standards Program. He is also Director of the National Materials and Structures Technology Management Center at ORNL.

During his 25 years at ORNL, Dr. Harms has served in various capacities, including Section Chief in the Metals and Ceramics Division for Fast Reactor Fuels and Materials Development, Head of the Ceramics Laboratory, and Director of the High Temperature Materials Program and the Isotopic Fuel and Materials Program for space nuclear applications.

In 1978 and 1979, Dr. Harms was a member of the International Nuclear Fuel Cycle Evaluation (INFCE) Program Working Group on Fast Breeder Systems, with responsibility for the Fuel Cycle Area.

Dr. Harms received his B.S. in Metallurgical Engineering from Wayne University and his M.S. and Ph.D. in Physical Metallurgy from the University of Minnesota. From 1955 to 1960, he was Associate Professor of Metallurgical Engineering at the University of Tennessee, Knoxville.

Dr. Harms is the author of 23 publications, principally on nuclear reactor technology and the fuel cycle. He has served on the Committee on Tubing and the Panel on Vanadium of the National Materials Advisory Board of the National Research Council. He is a fellow in the American Society for Metals and the American Nuclear Society, and is a member of Sigma Xi and other professional societies.

Mrs. LLOYD. Dr. Harms, thank you for your very excellent testimony and we'll have questions for both of you at the conclusion of Dr. Powell's testimony.

You may proceed, Dr. Powell.

STATEMENT OF DR. JAMES R. POWELL, HEAD, REACTOR SYSTEMS OFFICE, DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY

Dr. POWELL. Thank you, Madam Chairman.

I wish to thank you for the invitation to speak to you today to describe studies at Brookhaven National Laborabory on space nuclear power systems.

For the past several years, the department of nuclear energy at Brookhaven has been studying compact nuclear reactors for space power. These use the technology of the high-temperature gas-cooled reactor as a starting point.

Our studies have been directed toward producing space reactor designs capable of delivering a wide range of output powers with a single technology. All the space concepts and systems we work on are compact, appear reliable, operate at fairly high temperatures, and designed to be as safe as is practicle throughout the reactor lifetime. Beyond these desirable attributes, an effort has been made to use an extrapolation of existing high-temperature gas-cooled fuel and to keep the reactor and power conversion system as simple as is possible.

In discussing space power reactors one must keep in mind that two fundamentally different sorts of demands will be placed upon this class of energy sources. First, low-burnup, high-power applications; for example, direct thrusting with a nuclear rocket, may operate at a full power for times of minutes to hours. Second, base-load power for large satellites and space stations will require years of full power operation. It appears that the first sort of reactor will operate in an open cycle with expendable coolant while the second will operate in a closed cycle and reject energy to space radiatively.

A detailed description of our work is presented in the paper "Particle Bed Reactors and Related Concepts," which appears in the recent National Academy of Sciences Symposium on Advanced Compact Reactor Systems. I shall briefly summarize the work described therein and its relevance to space-power needs.

High-power, short-operating-life reactors differ from lower power, continuous-generation reactors, though they can have basically similar technology.

High-power systems probably will be cooled by hydrogen with direct exhaust of waste coolant to space. This open-cycle mode needs no heat radiator. Eliminating the radiator results in a much simpler and lighter power system. Conversion efficiency in the open cycle is projected to be from 40 to 50 percent thermal energy to electrical.

Open-cycle reactors will have to operate at high temperatures to minimize expenditure of coolant mass. Maximum temperature will be set by materials and/or power conversion equipment, such as a turbine.

Continuous or semicontinuous systems will have to operate for months to years. Exhausting coolant to space would make these systems unacceptably massive. Coolant must be continually recirculated and not lost to space.

In closed-cycle systems, only part of the thermal power generated in the reactor is converted to electrical power. Efficiency depends on the choice of conversion cycle and operating parameters, but typically is in the range of 10 to 30 percent. Waste energy not converted to electricity must be radiated to space. On Earth, the waste energy is simply absorbed in the ambient atmosphere or water.

The radiator usually dominates the weight of the power system. Radiator size and weight are reduced by operating at high temperatures and high efficiencies. For instance, doubling the absolute temperature of the radiator decreases the exposed surface requirement by nearly a factor of 16. The radiator for a 30-percent power cycle is roughly one-fourth the size and weight of that for a 10-percent-efficient cycle at the same output power.

The recent invention by Prof. Abraham Hertzberg at the University of Washington of a new type of space radiator holds great promise for lightweight, high-continuous, space-power systems. This concept, termed the liquid droplet radiator, radiates energy from a thin sheet of liquid drops. The drops are sprayed from an emitter toward a collector, radiating to space. The collected liquid is reheated by waste heat from the power cycle and then returned to the emitter.

The liquid droplet radiator offers to be lighter than finned-tube or heat pipe radiators. It has additional advantages of high survivability against meteoroids.

High power in space will be an enabling technology for many new applications. The current absence of such sources tends to inhibit thinking about what could be done if power were available.

At present, only small mass cargoes can be lifted from low-Earth orbit to high orbits, such as the geosynchronous orbit. Propellant consumption per unit mass is high and the capacity of the shuttle to carry up propellant is limited. Both act to constrain orbit transfer capability.

Development of orbit transfer tugs powered by space reactors would greatly increase orbit transfer capability. Electrically powered thrusters can operate at high specific impulse—2,000 to 3,000 seconds—which will allow propellant consumption for orbit transfer to be reduced. This will allow a corresponding increase in orbit transfer cargo capacity.

To achieve transfer times of 1 to 2 months with payloads of tens of tons, a tug will require on the order of 10 megawatts electric. A nuclear-powered tug could make several round trips per year and would greatly enhance operational capability in space.

Generation of hydrogen/oxygen fuels in space using nuclear power is being investigated by Grumman Aerospace Corp. For many missions, the shuttle transport system will be volume limited rather than weight limited. Substantial amounts of water could be carried into low-Earth orbit with minimal penalty on mission capability. This water could then be electrolyzed at a central satellite to hydrogen and oxygen and then liquified. The liquified hydrogen and oxygen would be distributed for various purposes. One impor-

tant application would be the supply of fuel for Centaur-type rockets for orbit transfer. Hydrogen/oxygen fuel could also be used for base-load or peak-load generation in small satellites in the Van Allen Belt, where solar cells may not be suitable.

Fuels production could be carried out at manned space stations, using part of the output from a continuous nuclear power system. Five electric megawatts, for example, would produce about 10 tons of liquid hydrogen and oxygen per day. This could service many power and propulsion users.

Manned space stations will require power for station keeping, orbit maneuvers with electric thrusters, communications, and radar. Though these individual uses may be relatively small, they can sum to a total of several hundred kilowatts electric.

Much larger amounts of power would be required for space manufacturing. Space manufacturing, including the production of new alloys and zero-gravity purification processes, will demand substantial power if practiced on a significant scale. Multimegawatt, economically viable power sources may be needed for space manufacturing. Nuclear reactors appear to be the only practical choice for this application.

High-resolution, space-based radar could greatly improve weather forecasting through its ability to spatially resolve fine detail in weather systems and follow it in real time. As with the other applications, multimegawatt electric power sources are required, and nuclear reactors appear to be the only practical choice.

Studies of lunar-based operations indicate that high powers—tens of megawatts electric—will be required for materials processing, life support, and communications. An important, relatively near-term application is the processing of ilmenite ore to extract oxygen. The oxygen could be transported to near-Earth orbits in liquid form, and used as an oxidizer with liquid hydrogen that would be lifted from Earth. Studies indicate that the useful payload lift capacity of the shuttle transport system would be doubled or tripled if lunar derived liquid oxygen were available.

Brookhaven studies have concentrated on space reactors based on technology developed for the high-temperature, gas-cooled reactor, including the particular fuel pioneered by GA Technologies and other organizations and laboratories. The fuel consists of small spheres, which are typically fabricated with a diameter from .05 to 0.1 centimeter. Each fuel sphere has a small central kernel of uranium carbide or oxide and is coated with several layers of impervious, high-temperature refractory materials.

There are basically two types of fuel particles used in high-temperature, gas-cooled reactors. The TRISO particle has a kernel of fully-enriched uranium covered with a porous layer of pyrographite. The porous layer provides void space for the fussion product gases produced by fission reactions. The outer layers of dense pyrographite and silicon carbide act as a small pressure vessel to contain gaseous and other fission products. Particles can be designed to have high burnup—50 percent or more—of the uranium fuel and retain virtually all the fission products.

The simpler BISO particles have a large kernel covered with a relatively thin coat of porous pryocarbon and a thin outer layer of pyrographite. BISO particles are used to breed new fissile uranium

by neutron absorption in thorium oxide. In a space reactor with low burnup, BISO-type particles could be used with enriched U^{235} kernels.

The Brookhaven continuous power reactors would use existing TRISO fuel particles, while the pulsed, high-power designs would use BISO-type particles. The latter would be modified to have zirconium carbide coatings instead of pyrographite. This would prevent reaction of the H_2 coolant with the particles.

High-temperature, gas-cooled reactor fuel particles have been used in various reactors. They are produced commercially and suppliers are available. Fuel properties have been well characterized. The particles have excellent radiation damage behavior; they achieve high burnups with only minor degradation and release of fission products.

Present particulate fuel has a very high-temperature capability. TRISO particles now operate for years at temperatures up to 1,500 Kelvins. This temperature level allows for efficient power conversion. First generation systems would probably be designed to use existing TRISO fuel. Fuel temperatures of 2,000 Kelvins should be achievable by using improved particle coatings. These higher temperatures would allow increased thermal efficiency and reduced radiator weight.

Present TRISO or BISO fuel particles are not suitable for open-cycle reactors since their graphite coatings will react with the hydrogen coolant. However, the particles can be modified to have zirconium carbide coatings, which should not significantly react with hydrogen over the operating life of the reactor—a few hours. GA Technologies has made zirconium-carbide coated fuel.

Outlet temperature in open-cycle reactors should be as high as possible to keep coolant mass expenditures as low as possible. At present, turbine inlet temperature appears to be the limiting factor.

Brookhaven reactor designs differ from conventional HTGR's in two major respects. First, the small fuel particles are directly cooled by gas, instead of being imbedded in large blocks or spheres of graphite. Direct cooling greatly increases the surface area for heat transfer, so that the power density—watts per liter—can be hundreds of times that in conventional HTGR's. Analyses and experiments indicate that power densities of megawatts per liter of fuel can be achieved in these types of particle bed reactors, a necessary condition for compact systems.

The second major difference is that in the Brookhaven reactors, the fuel particles are not mixed with the moderator, but are kept separate. This allows the use of better moderators such as zirconium hydride or beryllium. These materials have stronger neutron moderating capability than graphite, and can greatly reduce reactor size.

Two types of reactors are being studied. Both use particulate fuel, but contain them differently. In the first type, the fixed bed reactor, fuel particles are packed between two porous screens or frits. Cool gas enters the packed bed through the inlet frit, is heated by the fuel particles, and then exits through the hot outlet frit.

In one configuration, the fuel particles are packed into a single, large annular bed, with an outer moderator of beryllium and an inner moderator of graphite. Coolant radiates inward through the bed, with the hot gas exiting from an innerplenum next to the hot frit.

I've brought along a model showing how this is constructed. This is a quarter-scale model of a high-power space reactor using that type of construction in HTGR particulate fuel.

Mrs. LLOYD. Dr. Powell, would you hold that up so the participants in the audience could see it also, please.

Dr. POWELL. Certainly.

Basically we have an outer moderator of helium, an annular fuel bed of particles, and inner moderator of graphite with helium flow through the particle bed. The particles are contained between two frits, one of which is cold and the other which is hot. This is a quarter-scale model. The reactor would put out 50 megawatts thermal with helium cooling and 200 megawatts with hydrogen cooling.

Mr. LUJAN. Is that design quarter scale?

Dr. POWELL. Quarter scale.

Mr. MACKAY. It would be four times that big?

Dr. POWELL. Yes.

The fixed bed reactor is a thermal reactor. Fission neutrons are moderated in the outer and inner reflectors, and diffuse back to the fuel bed. Control is by movable poison rods or drums in the outer reflector. The long neutron lifetime in externally moderated reactors makes the fixed bed reactor more sluggish neutronically and easier to control.

An alternate version of this concept uses multiple annular bed elements. These are placed in a moderator matrix so it would look much more like a conventional reactor. Coolant would flow radially inward through each annular and exit through the internal channel to a common outlet duct. Gas distribution plenums surround each packed bed element.

Fixed bed reactors can be used for both long-life continuous generation and short-life pulsed generation. Reactor size and weight will depend on power and the degree of burnup. Typically, reactor diameter and length, including reflector, will range between about a half meter for low powers to about 1¼ meters for high powers. Reactor weights will range from about one-half to 3 tons, depending on the power level and the burnup time.

Continuous or semicontinuous fixed bed reactors with helium coolant could deliver up to about 100 megawatts electric. For pulsed generation, the fixed bed reactors with hydrogen coolant could deliver up to about 400 megawatts electric.

Experiments on electrically heated HTGR fuel particle beds have been carried out at Brookhaven using helium coolant. In these experiments, power densities of 1 megawatt per liter have been demonstrated using a low-pressure helium coolant. This power density should be adequate for practical systems. Higher power density can be achieved with higher coolant pressures. Design pressures up to 40 atmospheres are considered. Experiments in this regime are planned for the near future.

Fuel particle beds have operated at temperatures up to 1,700 kelvins, which is more than required for a first-generation reactor, but

for relatively short times. We haven't done lifetime tests. Particle beds have been repeatedly ramped to full temperature and power in very short times—approximately 3 seconds—without damage.

The rotating bed reactor is the second type of compact reactor under investigation at Brookhaven. The fuel particles are held by centrifugal force inside a rotating, coolporous frit. Inlet coolant enters from a plenum between the rotating frit and the external moderator/reflector. It then passes through the particle fuel bed into the internal central cavity, and exits through a nozzle at one end of the reactor.

The rotating bed would look much like the model, except it would have an internal moderator and the outer frit would rotate as in a centrifugal separator.

This reactor concept is designed to generate up to much higher power levels and much higher temperatures, perhaps as much as 5,000 megawatts thermal and as much as 3,000 kelvin. It could be used for direct thrust for orbit transfers—as a classic nuclear rocket was designed for—or for electric generating using MHD or very high-temperature turbines.

Half-scale cold flow models of the rotating bed reactor have been tested. The rotating bed was stable at high gas flow rates and large centrifugal forces, up to thousands of g's. The bed was operated in a settled, partly fluidized, or fully fluidized mode without loss of particles.

In principal, for these particle bed reactors, it is feasible to remotely load and unload fuel particles. If this proves practical, it would have important advantages for safety and reliability.

Space reactors could then be launched without fuel, eliminating concern about criticality accidents during launch and ascent into orbit. Fuel would be carried on separate small boosters from an isolated launch site. After the fuel containers rendezvous with the orbiting reactor system, the particles could be pneumatically transferred to the reactor. After remote loading, the reactor could be started when desired.

Similarly, fuel could be unloaded into a shielded, passively cooled storage cask. This would allow limited access to the power system for maintenance and/or repair. Also, fresh fuel could be loaded to extend operating life.

Experiments are planned to examine the capability of pneumatically loading and unloading simulated fixed bed reactors.

If this remote loading/unloading in space proves impractical, particle bed reactors would be launched already fueled. In this event, they would have comparable safety features to those of other fixed fuel reactor concepts and would have to address the same safety and reliabilty issues.

These issues include prevention of accidental criticality during launch and ascent; multiple independent shutdown systems; avoidance of unplanned reentry; and satisfactory ultimate waste disposal.

These issues can be resolved for particle bed reactors, and for other types of reactors, given the appropriate design and operating guidelines. Control of particle bed reactors would use multiple, independent movable poison elements in the outer reflector. An anticriticality system for use during launch/ascent accidents would in-

volve the fast pneumatic injection of neutron absorbing particles—that is boron-carbide—into the inlet coolant plenum. This would insure subcriticality against any conceivable accident, including explosion of the launch vehicle, fires, high velocity impact, water immersion.

Though the particle bed reactor designs use available technology as much as possible, considerable development will still be required for the various reactor and power system components. This includes work on such items as neutronics, thermonhydraulics, turbines, radiators and so forth. It must be remembered that this is still a reactor concept based to our best extent on existing technology, but requiring substantial development.

However, to date we have not identified any fundamentally no-go or go-type issues to resolve and we feel the development needs can be relatively well defined.

For the closed-cycle, helium-cooled particle bed reactor, the principal requirement is a demonstration of satisfactory high-temperature frit. The hot frit should be compatible with the fuel particles over the life of the reactor, and have adequate mechanical strength at operating temperature. From preliminary analyses and tests, metal frits appear satisfactory for temperatures up to 1,300 to 1,400° kelvins. Nonmetal frits may be suitable and would allow higher temperatures. Both types of frits require further study, design, and testing.

First generation fuel would be based upon commercial TRISO particles. These particles are well characterized and can be used to approximately 1,500 kelvin. Other reactor materials should be tested, but these do not represent major technical risks. Verification testing should be carried out, however.

There is extensive experience on turbines, compressors, and generators that are relevant to the power cycle. Engineering development of the specific configurations is necessary. Uncooled refractory metal or ceramic blading may be needed for the turbine, though cooled-blade technology is also an option.

After the reactor, the component of the power system requiring the most development is probably the waste heat radiator. For powers up to 1 to 2 megawatts electric, finned-tube or heat pipe radiators will probably be chosen. For higher powers, liquid droplet radiators or some other type of advanced lightweight radiator is probably mandatory.

Brookhaven has proposed the construction and test of a full-scale, full-power simulated nonnuclear space reactor system. It would test the operation of the prototype reactor and power conversion system at the operating conditions expected for the actual space device, with the materials and dimensions. It would use actual TRISO particles but not enriched, and the particle bed would be heated electrically, as in our experiments with smaller beds, by an electric current rather than by nuclear reactions. In this experiment nominal thermal power would be ten megawatts, with an output of about 3 megawatts electric from the generator.

The experiment would provide valuable operating experience on a simulated space power system. Only the nuclear performance would not be tested. However, the performance of the fuel bed would need to be simulated in critical experiments. With informa-

tion from this experiment, irradiation experience, and critical experiments, there should be sufficient knowledge to proceed with the design of a full-scale, ground-based space reactor prototype system.

The electrically heated core experiment could be operating in approximately 3 years, given adequate funding. The full-scale nuclear reactor system would take at least an additional 4 to 6 years.

The open-cycle, hydrogen-cooled particle bed reactor will require development work on the zirconium carbide coated fuel and the high-temperature frit. Materials should be validated for operation in an environment of hot hydrogen and neutron irradiation.

The high-power outputs associated with the open-cycle system will necessitate development work on the turbine and generator. Turbines produced for the Apollo program can be adapted to generate approximately 50 megawatts; higher power levels could be achievable with additional development. A lightweight, 20-megawatt superconducting generator is currently under development at the AeroPropulsion Laboratory. Generator capability can be expanded to higher powers—50 megawatts—with design modifications. Multiple turbogenerators can also be used if higher power outputs are desired than is practical with a single unit.

An electrically heated, nonnuclear prototype will be required for the open-cycle system as well. It would demonstrate integrated operation of the reactor core and the power system using hydrogen coolant. Full-scale operation may not be required.

This concludes my prepared statement, Madam Chairman. I wish to thank you for the opportunity to present this.

[The prepared statement by Dr. Powell follows:]

Statement of
James R. Powell
Head, Reactor Systems Office
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, NY 11973
Before the

Subcommittee on Energy Research and Production
Committee on Science and Technology
U.S. House of Representatives

Madam Chairman and Members of the Subcommittee:

I wish to thank you for the invitation to speak to you today to describe studies at Brookhaven National Laboratory on space nuclear power systems.

INTRODUCTORY COMMENTS

For the past several years, the Department of Nuclear Energy at Brookhaven National Laboratory has been studying compact nuclear reactors for space power. These use the technology of the High-Temperature Gas-Cooled Reactor as a starting point.

Studies carried out at Brookhaven have been directed toward producing space reactor designs capable of delivering a wide range of output powers with a single technology. All space reactor concepts and systems are compact, apparently reliable, operate at fairly high temperatures, and designed to be as safe as is practicle throughout the reactor lifetime. Beyond these desirable attributes, an effort has been made to use an extrapolation of existing High-Temperature Gas-Cooled Fuel and keep reactor and power conversion systems as simple as is possible.

In discussing space power reactors one must keep in mind that two fundamentally different sorts of demands will be placed upon this class of energy sources. Firstly, low-burnup; high-power applications (e.g., direct thrusting with a nuclear rocket such as NERVA) may only operate at full power for times of minutes to hours. Secondly, base-load power for large satellites and space stations will require years of full power operation. It appears that the first sort of reactor will operate in an open cycle with expendable coolant while the second will operate in a closed cycle and reject energy to space radiatively.

A detailed description of Brookhaven's work is presented in the paper "Particle Bed Reactors and Related Concepts," which appears in the recent National Academy of Sciences Symposium on Advanced Compact Reactor Systems. I shall briefly summarize the work described therein and its relevance to turbine space-power needs.

POWER LEVEL AND OPERATING LIFE

High power, short operating life reactors differ from lower power, continuous generation reactors, though they can have basically similar technology.

High-power systems probably will be cooled by hydrogen with direct exhaust of waste coolant to space. This open-cycle mode needs no waste heat radiator. Eliminating the radiator results in a much simpler and lighter power system. Conversion efficiency in the open cycle are projected to be typically from 40 to 50% (thermal energy to electrical).

Open-cycle reactors will have to operate at high temperatures to minimize expenditure of coolant mass. Maximum temperature will be set by materials and/or power conversion equipment (i.e., the turbine).

Continuous or semi-continuous systems will have to operate for months to years. Exhausting coolant to space would these make systems unacceptably massive. Coolant would be continually recirculated and not lost to space.

In closed-cycle systems, only part of the thermal power generated in the reactor is converted to electrical power. Efficiency depends on the choice of conversion cycle and operating parameters, but typically is in the range of 10 to 30%. Waste energy not converted to electricity must be radiated to space (on earth, the waste energy is simply absorbed in the ambient atmosphere or water).

The radiator usually dominates the weight of the power system. Radiator size and weight are reduced by operating at high temperatures and high efficiencies. For instance, doubling the absolute temperature of the radiator decreases its exposed surface requirement by nearly a factor of sixteen. The radiator for a 30% efficient power cycle is roughly one-fourth the size and weight of that for a 10% efficient cycle at the same output power.

The recent invention by Professor Abraham Hertzberg at the University of Washington of a new type of space radiator holds great promise for lightweight, high-continuous space-power systems. This concept, termed the Liquid Droplet Radiator, radiates energy from a thin sheet of liquid drops. The drops are sprayed from an emitter toward a collector, radiating to space. The collected liquid is reheated by waste heat from the power cycle and then returned to the emitter.

The Liquid Droplet Radiator offers to be lighter than finned-tube or heat pipe radiators. It has additional advantages of high survivability against meteoroids.

APPLICATIONS

High power in space will be an enabling technology for many new applications. The current absence of such sources tends to inhibit thinking about what could be done if power were available.

At present, only small mass cargoes can be lifted from low-earth orbit to high orbits, such as the geosynchronous orbit. Propellant consumption per unit mass is high and the capacity of the shuttle to carry up propellant is limited. Both act to constrain orbit transfer capability.

Development of orbit transfer tugs powered by space reactors would greatly increase orbit transfer capability. Electrically-powered thrusters can operate at high specific impulse (i.e., 2000 to 3000 seconds), which will allow propellant consumption for orbit transfer to be reduced. This will allow a corresponding increase in orbit transfer cargo capacity.

To achieve transfer times of one to two months with payloads of tens of tons, a tug will require on the order of ten megawatts-electric. A nuclear-powered tug could make several round trips per year and would greatly enhance operational capability in space.

Generation of hydrogen/oxygen fuels in space using nuclear power is being investigated by Grumman Aerospace Corporation. For many missions, the Shuttle Transport System will be volume-limited rather than weight-limited. Substantial amounts of water could be carried into low-earth orbit with minimal penalty on mission capability. This water could then be electrolyzed at a central satellite to hydrogen and oxygen and then liquified. The liquified hydrogen and oxygen would be distributed for various purposes. One important application would be the supply of fuel for Centaur-type rockets for orbit transfer. Hydrogen/oxygen fuel could also be used for base-load or peak-load generation in small satellites in the Van Allen Belt, where solar cells may not be suitable.

Fuels production could be carried out at manned space stations, using part of the output from a continuous nuclear power system. Five electric megawatts, for example, would produce about ten tons of liquid hydrogen and oxygen per day. This could service many power and propulsion users.

Manned-space stations, also will require power for station keeping, orbit maneuvers with electric thrusters, communications, and radar. Though these individual uses may be relatively small, they can sum to a total of several hundred kilowatts electric.

Much larger amounts of power would be required for space manufacturing. Space manufacturing, including the production of new alloys and zero-g purification processes, will demand substantial power if practiced on a significant scale. Multimegawatt, economically viable power sources may be needed for space manufacturing. Nuclear reactors appear to be the only practical choice for this application.

High resolution space-based radar could greatly improve weather forecasting through its ability to spatially resolve fine detail in weather systems and follow it in real time. As with the other applications, multimegawatt electric power sources are required, and nuclear reactors appear to be the only practical choice.

Studies of Lunar-Based operations indicate that high powers, i.e., tens of megawatts-electric, will be required for materials processing, life support, and communications. An important, relatively near-term application is the processing of ilmenite ore to extract oxygen. The oxygen could be transported to near-earth orbits in liquid form, and used as an oxidizer with liquid hydrogen that would be lifted from earth. Studies indicate that the useful payload lift capacity of the shuttle transport system would be doubled or tripled if a lunar-derived liquid oxygen were available.

PARTICLE BED REACTORS

Brookhaven National Laboratory studies have concentrated on space reactors based on technology developed for the High Temperature Gas-Cooled Reactor, including the particulate fuel pioneered by GA Technologies and other organizations and laboratories. This fuel consists of small spheres, which are

typically fabricated with a diameter from 0.05 to 0.1 cm (one five-hundredth to one two-hundredth of an inch). Each fuel sphere has a small central kernel of uranium carbide or oxide and is coated with several layers of impervious, high-temperature refractory materials.

There are basically two types of fuel particles used in High-Temperature Gas-Cooled Reactors. The TRISO particle has a kernel of fully-enriched uranium (^{235}U), oxide or carbide covered with a porous layer of pyrographite. The porous layer provides void space for the fisson product gases produced by fission reactions. The outer layers of dense pyrographite and silicon carbide act as a small "pressure vessel" to contain the gaseous and other fission products. Particles can be designed to have high burnup, 50% or more, of the uranium fuel, and virtually complete retention (99.9%) of the fission products.

The simpler BISO particles have a large kernel covered with a relatively thin coat of porous pyrocarbon and a thin outer layer of pyrographite. BISO particles are used to breed new fissile uranium by neutron absorption in thorium oxide. In a space reactor with low burnup, BISO-type particles could be used with enriched ^{235}U kernels.

The Brookhaven continuous power reactors would use existing TRISO fuel particles, while the pulsed, high-power designs would use BISO-type particles. The latter would be modified to have zirconium carbide coatings instead of pyrographite. This would prevent reaction of the H_2 coolant with the particles.

High-Temperature Gas-Cooled Reactor fuel particles have been used in various reactors. They are produced commercially and suppliers are available. Fuel properties have been well characterized. The particles have excellent radiation damage behaviour; they achieve high burnups with only minor degradation and release of fission products.

Present particulate fuel has a very high-temperature capability. TRISO particles now operate for years at temperatures up to 1500 Kelvins (2200 degrees Fahrenheit). This temperature level allows for efficient power conversion. First generation systems would probably be designed to use existing TRISO fuel. Fuel temperatures of 2000 Kelvins (3100 degrees Fahrenheit) should be achievable by using improved particle coatings. These higher temperatures would allow increased thermal efficiency and reduced radiator weight.

Present TRISO or BISO fuel particles are not suitable for open-cycle reactors since their graphite coatings will react with the hydrogen coolant. However, the particles can be modified to have zirconium carbide coatings, which should not significantly react with hydrogen over the operating life of the reactor, i.e., a few hours. GA Technologies has made zironium-carbide coated fuel.

Outlet temperature in open-cycle reactors should be as high as possible to keep coolant mass expenditure as low as possible. At present, turbine inlet temperature appears to be limiting.

Brookhaven National Laboratory reactor designs differ from conventional High-Temperature Gas-Cooled Reactors in two major respects. First, the small fuel particles are directly cooled by gas, instead of being imbedded in large blocks or spheres of graphite. Direct cooling greatly increases the surface

area for heat transfer, so that power density (i.e., watts per liter) can be hundreds of times that in conventional High-Temperature, Gas-Cooled Reactors. Analyses and experiments indicate that power densities of megawatts per liter of fuel can be achieved in the Brookhaven reactor concepts, a necessary condition for compact systems.

The second major difference is that in the Brookhaven reactors, the fuel particles are not mixed with the moderator, but are kept separate. This allows the use of better moderators such as zirconium hydride or beryllium. These materials have stronger neutron moderating capability than graphite, and can greatly reduce reactor size.

Two types of reactors are being studied at Brookhaven. Both use particulate fuel, but contain them differently. In the first type, the Fixed Bed Reactor, fuel particles are packed between two porous screens or "frits." Cool gas enters the packed bed through the inlet frit, is heated by the fuel particles, and then exits through the hot outlet frit.

In one configuration, the fuel particles are packed into a single, large annular bed, with an outer moderator of beryllium and an inner moderator of graphite. Coolant flows radially inwards through the bed, with the hot gas exiting from an inner plenum next to the hot frit.

The Fixed Bed Reactor is a thermal reactor; fission neutrons are moderated in the outer and inner reflectors, and diffuse back to the fuel bed. Control is by movable poison rods or drums in the outer reflector. The long-neutron lifetime in externally-moderated reactors makes the Fixed Bed Reactor more sluggish neutronically and easy to control.

An alternate version of this concept uses multiple annular bed elements. These are placed in a moderator matrix (e.g., beryllium or zirconium hydride) with an external reflector. Coolant flows radially inward through each annular and exit through the internal channel to a common outlet duct. Gas distribution plenums surround each packed bed element.

Fixed Bed Reactors can be used for both long-life continuous generation and short-life pulsed generation. Reactor size and weight will depend on power and burnup level. Typically, reactor diameter and length (including reflector) will range between about one-half meter (20 inches) for low powers to one and a quarter meters (50 inches) for high powers. Reactor weights will range from about one-half to three tons, depending on size.

Continuous or semi-continuous Fixed Bed Reactors with helium coolant could deliver up to about 100 megawatts electric. For pulsed generation, the Fixed Bed Reactors with hydrogen coolant could deliver up to about 400 megawatts electric.

Experiments on electrically-heated High-Temperature Gas-Cooled Reactor particle beds have been carried out using helium coolant. In those experiments, power densities of one megawatt per liter have been demonstrated using low-pressure (approximately one atmosphere) helium coolant. This power density should be adequate for practical systems. Higher power density can be achieved with higher coolant pressures. Design pressures up to 40 atmospheres are considered. Experiments in this regime are planned for the near future.

Fuel particle beds have operated at temperatures up to 1700 Kelvins (2600 degrees Fahrenheit), which is more than required for a first-generation reactor. Particle beds have been repeatedly ramped to full temperature and power in very short times (approximately three seconds) without damage.

The Rotating Bed Reactor is the second type of compact reactor under investigation at Brookhaven. The fuel particles are held by centrifugal force inside a rotating, cool-porous frit. Inlet coolant enters from a plenum between the rotating frit and the external moderator/reflector, passes through the particle fuel bed into the inner central cavity, and then exits through a nozzle at one end of the reactor.

This reactor concept is designed to generate up to 5000 megawatts-thermal at temperatures up to about 3000 K. It could be used for direct thrust for orbit transfer (as a classic nuclear rocket) or for electric generation using MHD or high-temperature turbines.

Half-scale cold flow models of the Rotating Bed Reactor have been tested. The rotating bed was stable at high gas flow rates and large centrifugal forces, up to thousands of g's. The bed can operate in a settled, partly-fluidized, or fully-fluidized mode without loss of particles.

SAFETY AND RELIABILITY

In principal, it is feasible to remotely load and unload fuel particles from Brookhaven designed particle bed reactors. If this proves practical, it would have important advantages for safety and reliability.

Space reactors could then be launched without fuel, eliminating concern about criticality accidents during launch and ascent into orbit. Fuel would be carried on a separate small booster (or several boosters) from an isolated launch site.

After the fuel container(s) rendezvous with the orbiting reactor system, the particles could be pneumatically transferred to the reactor. After remote loading, the reactor would be started when desired.

Similarly, fuel could also be unloaded into a shielded, passively-cooled storage cask. This would allow limited access to the power system for maintenance and/or repair. Also, fresh fuel could be loaded to extend operating life.

Experiments are planned to demonstrate the capability of pneumatically loading and unloading simulated Fixed Bed Reactors.

If remote loading/unloading in space proves impractical, particle bed reactors would be launched already fueled. In this event, they would have comparable safety features to those for other fixed fuel reactor concepts and would have to address the same safety and reliability issues.

These issues include prevention of accidential criticality during launch and ascent; multiple independent shutdown systems; avoidance of unplanned reentry; and satisfactory ultimate waste disposal.

These issues can be resolved for particle bed reactors, given appropriate design and operating guidelines. Control of particle bed reactors would use multiple, independent movable poison elements in the outer reflector. An anti-criticality system for use during launch/ascent accidents would involve the fast pneumatic injection of neutron absorbing particles (e.g., boron-carbide) into the inlet coolant plenum. This would ensure subcriticality against any conceivable accident, including explosion of the launch vehicle, fires, high velocity impact, water immersion, etc.

Development Requirements

For the closed-cycle, helium-cooled particle bed reactor, the principal requirement is the demonstration of a satisfactory high-temperature frit. The hot frit should be compatible with the fuel particles over the life of the reactor, and have adequate mechanical strength at operating temperature. From preliminary analyses and tests, metal frits appear satisfactory for temperatures up to 1300 to 1400 Kelvins (1900 to 2100 degrees Fahrenheit). Non-metal frits (e.g., graphite) may be suitable and would allow higher temperatures. Both types of frits require further study, design, and testing.

First generation fuel would be based upon commercial TRISO particles. These particles are well characterized and can be used to approximately 1500 Kelvins (2300 degrees Fahrenheit). Other reactor materials should be tested, but these represent much smaller technical risks. Verification testing should be carried out, however.

There is extensive experience on turbines, compressors, and generators that are relevant to the power cycle. Engineering development of the specific configurations is necessary. Uncooled refractory metal or ceramic blading may be needed for the turbine, though cool-blade technology is also an option.

After the reactor, the component of the power system requiring the most development is probably the waste heat radiator. For powers up to one to two megawatts-electric finned-tube or heat pipe radiators will probably be chosen. For substantially higher powers, Liquid Droplet Radiators or some other type of lightweight radiator is probably mandatory.

Brookhaven National Laboratory has proposed the construction and test of a full-scale, full-power simulated (non-nuclear) space reactor system. It would test the operation of the prototype reactor and power conversion system at the operating conditions expected for the actual space device, with the same materials and dimensions. Actual TRISO fuel (non-enriched ^{235}U) would be used, but the particle bed would be heated electrically by a current rather than by nuclear reactions. Nominal thermal power would be ten megawatts, with an output of about three megawatts-electric from the generator.

The experiment would provide valuable operating experience on a simulated space power system. Only the nuclear performance would not be tested. However, the performance of the fuel bed would need to be simulated in critical experiments. With information from this experiment, irradiation experience, and critical experiments, there would be sufficient knowledge to proceed with the design of a full-scale, ground-based space reactor prototype system.

The electrically-heated core experiment could be operating in approximately three years, given adequate funding. The full-scale nuclear reactor system would take at least an additional four to six years.

The open-cycle, hydrogen-cooled particle bed reactor will require development work on the zirconium-carbide coated fuel and the high-temperature frit. Materials should be validated for operation in an environment of hot hydrogen and neutron irradiation.

The high power outputs associated with the open-cycle system will necessitate development work on the turbine and generator. Turbines produced for the Apollo program can be adapted to generate approximately 50 megawatts; higher power levels should be achievable with additional development. A lightweight, 20-megawatt superconducting generator is currently under development at the AeroPropulsion Laboratory. Generator capability can be expanded to higher powers, e.g., 50 megawatts, with design modifications. Multiple turbo-generators can also be used if higher power outputs are desired than is practical with a single unit.

An electrically-heated, non-nuclear prototype will be required for the open-cycle system as well. It would demonstrate integrated operation of the reactor core and the power system using hydrogen coolant. Full-scale operation may not be required.

This concludes my prepared statement, Madam Chairman. Again, I wish to thank the committee for the opportunity to present these matters.

Mrs. LLOYD. Thank you, Dr. Powell, for your very excellent testimony. We appreciate your input today. It seems to me we have almost an unlimited means to make the most of our applications on the civilian program as well.

Dr. Harms, you were also a participant in the SNAP program, I believe. What are some of the transfers that you can envision from that program to the SP-100 program?

Dr. HARMS. The SNAP programs that ORNL participated in were SNAP-2, SNAP-8, SNAP-10A, and SNAP-50, all of which, it turns out, involved liquid metal as coolant or working fluid. All of the information generated of liquid metals is very useful to the present program. In addition, in the more advanced program, SNAP-50, and in the NASA advanced program which followed significant advanced fuels development and irradiation testing were carried out. The advanced fuel was uranium-nitride, as compared with uranium-oxide, the more conventional fuel, and the cladding was a tantalum-base alloy. Also, at such sites as General Electric, there were extensive large-component tests in lithium-cooled systems for as long as 10,000 hours and endurances tests, as I recall, of around 5,000 hours on turbines for use in boiling potassium systems. In addition, there were full-scale boiler tests from which important heat transfer data were derived. So this experience is very useful; yes.

Mrs. LLOYD. Reactors and the metals as well as the fuels will require additional R&D work.

In addition to these areas, where do you see the need for critical R&D in other subsystems?

Dr. HARMS. As currently defined, I believe, the reactor subsystem does not include the shielding subsystem, and that's one item that I have included in my written testimony that I didn't discuss in my oral presentation. The shielding subsystem is very important because the size of the shielding may dominate the whole situation. There needs to be work done in that area, and I might point out that we at once have the only facility—in the country—the tower shileding facility—for carrying out such work. We also have at that facility a modified SNAP-10A reactor, the only space reactor around, on which we performed some experiments in the midseventies.

Mrs. LLOYD. In your Phase I report, that you submitted to DOE, you alluded to the critical technical problems that must be resolved to bring to fruition the space reactor power systems. It seems to me that the two-phase zero-gravity problem was a very complex one and that you have a lot of problems to resolve in this area. Would it be better to concentrate our R&D efforts on those systems which would not have this problem?

Dr. HARMS. Well, first, my answer to your question is, "No," and the reason is that there is just too much benefit to be derived from the Rankine-cycle system. I point out again that the SNAP-50 and the advanced systems all employed that type of power conversion.

Mrs. LLOYD. I didn't say that in a critical manner. I wanted to know the information.

Dr. HARMS. What information?

Mrs. LLOYD. I was asking if you might expand on that.

Dr. HARMS. Oh, the kind of information that needs to be developed. Like in the near zero gravity experiment?

Mrs. LLOYD. That's correct.

Dr. HARMS. That experiment has to do strictly with the behavior of the two phases in the nongravitational field—just as the astronaut and this piece of bacon kind of float the same way even though we consider that the astronaut is probably denser than the bacon. The vapor and the liquid would behave in a similar manner. As I have mentioned, the corrective devices that could be used are in place, and many have been demonstrated in aircraft trajectory experiments that were performed in the early seventies. It's just a matter of verifying and validating those experiments in a test of much longer duration—longer than just the 40 to 50 seconds available in an aircraft trajectory test—such as one could achieve in a space shuttle experiment.

Mrs. LLOYD. Thank you. I could go on but I think our time is going to be a little bit limited.

Dr. Powell, your reactor design is certainly intriguing to this subcommittee because of its close relationship to the HTGR, the design which this committee has supported for some time. How would such a system package in the space transportation system, and are you providing information to NASA-Lewis?

Dr. POWELL. Yes; the reactor and shield will be very small, compared to the shuttle bay volume. What really will dominate is the power system and the radiator system. That will probably set the limit as to how you can pack it in the shuttle. Our designs have been primarily oriented toward high-power systems. For that we've examined mostly options like the liquid drop radiator which can be packaged. It's a nonfixed radiator which can be extended to have the liquid drops radiating the heat to space.

If you have to go to a fixed structure radiator configuration, it will be a much more limiting state of affairs and I would say that you would be not able to boost as much power capability in the single shuttle launch with that type of system.

Mrs. LLOYD. I would like a little bit of information on your funding picture. Are you receiving your funds from DOE or DOD?

Dr. POWELL. At this point we're not funded. We were funded by the Rocket Propulsion Laboratory and——

Mrs. LLOYD. You did not receive any fiscal year 1983 funding?

Dr. POWELL. We received some but that has run out.

Mrs. LLOYD. Dr. Harms, have you received any of the 1983 funding?

Dr. HARMS. We have no SP-100 funding at the present time, although we did have funding directly from DOE for the studies that I described in my testimony.

Mrs. LLOYD. Thank you very much.

Mr. Lujan?

Mr. LUJAN. Thank you, Madam Chairman.

I want to understand this space reactor and how it differs. I gather the first thing is size. Certainly it's going to be a much, much smaller reactor than anything that we're used to seeing. This is a meter in diameter or length?

Dr. POWELL. On that order.

Mr. LUJAN. What's this, in 50 megawatts?

Dr. POWELL. For this particular one.

Dr. HARMS. The first order of business in the SP-100 program is a 100-kilowatt-class reactor, I would point out. The multimegawatt class is considered a longer term application.

Mr. LUJAN. Is the smaller one in power, smaller in size?

Dr. HARMS. It doesn't have to be but——

Mr. LUJAN. What does that mean in terms of compacting the size? I know there's probably not a 50-megawatt reactor around, what do we have? A 350, I guess, HTGR?

Dr. POWELL. Yes, it's 350 MWe, right.

Mr. LUJAN. How much bigger than that, more than seven times?

Dr. POWELL. It's much more than seven times.

Mr. LUJAN. It's really quite a job to bring it down to that size. Too, I guess, the liquid that is used inside. Is it a closed-loop sort of thing?

Dr. HARMS. Yes, sir.

Mr. LUJAN. And you have to use a different type of liquid other than water because of the gravity situation.

Dr. HARMS. No. The coolant is in one concept a liquid metal, and in the other concept it's a gas.

Mr. LUJAN. You prefer it to liquid metal?

Dr. HARMS. We happen to prefer the liquid metal.

Mr. LUJAN. Same kind of fuel?

Dr. HARMS. Well, it depends upon the requirements, sir. For the higher performance levels, one should go to a higher performance fuel such as uranium-nitride, which was studied rather extensively in the SNAP-50 and advanced NASA programs because of its higher uranium density. The uranium atoms are more closely packed in uranium-nitride fuel than they are in uranium dioxide.

Mr. LUJAN. Dr. Powell, is that the same kind of fuel that you're talking about in your——

Dr. POWELL. No; we would be using probably zirconium carbide coated fuel.

Mr. LUJAN. Would it be operating at substantially different temperatures than an onground reactor would be operating?

Dr. POWELL. Well, in our case we would operate the fuel at the same temperature it operates now in a reactor onground in the HTGR, but the power system would have to operate at considerably higher temperatures.

Mr. LUJAN. The steam?

Dr. POWELL. Not steam, but the gas; yes.

Mr. LUJAN. And that's why we need the different materials; to be able to withstand higher temperatures?

Dr. POWELL. Yes; we will need higher temperature advance materials to stand those higher temperatures.

Mr. LUJAN. The steam?

Dr. POWELL. Not steam, but the gas, yes.

Mr. LUJAN. And that.s why the different materials that we need, to be able to withstand higher temperatures?

Dr. POWELL. Yes. We will need higher temperature advance materials to stand those higher temperatures.

Mr. LUJAN. Do you have some problems with the kind of heat that you get in space environment? I'm not technical so when I

hear that one side of the Shuttle gets very hot and the other side is freezing—do you have those same problems with the space reactor?

Dr. POWELL. Well, there's the waste heat we have to get rid of and that has to be radiated to space. Because one wants to keep the mass of the radiator as small as possible, the radiator at as high a temperature as possible. That's why it drives everything up in terms of operating temperature.

Dr. HARMS. One process that takes place in the space environment, sir, that's quite different than on Earth is the volatilization of certain high vapor pressure elements, such as chromium, from these super alloys. They're simply lost, and that's to the detriment of the structural integrity of the super alloy which on Earth wouldn't have that problem.

Mr. LUJAN. These differences that we've spoken of, in very simple terms, are the basic differences as to why you need all this research into a space reactor?

Dr. HARMS. As I view it, it's because of the higher performance levels required, that is, the higher ratio of power to mass and the higher efficiencies that will be needed in both advanced civilian and military applications.

Mr. LUJAN. Dr. Powell, you talk about open-cycle reactors. Are you talking about those replacing the engines on the shuttles?

Dr. POWELL. No. The classic nuclear rocket was designed to take payloads from a high orbit to a much higher orbit and operate in a safe way. It would never be used for takeoffs from the ground.

Mr. LUJAN. One final question.

You were talking in your testimony about Brookhaven working on the construction of, and test of, a full-scale, full-power, nonnuclear—I'm skipping the word simulated for the moment, I hadn't read that when I started the question. Where would you get the power if it's going to be nonnuclear?

Dr. POWELL. Well, it really would be a simulated test and we would have to use existing power onsite to electrically heat the particles. This reactor has a nice feature in that you can heat the particles by passing a current through them to the same degree that one would heat them nuclearly, but it's not the same physical process.

Mr. LUJAN. I started asking the question before I saw some of the testimony. After rereading it I withdraw my question on that point.

Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Lujan.

Mr. MacKay?

Mr. MACKAY. Madam Chairman, I find this fascinating and I'm sort of in a come-from-behind effort. If I ask some questions that are sufficiently basic to demonstrate my total ignorance, I hope you'll forgive me.

Where are we in terms of years away from having that or something like that operational?

Dr. POWELL. Each person has his own particular degree of optimism. Mine would be 7 to 10 years given a strong program.

Mr. MACKAY. I gathered that where we need the additional research, in addition to shielding, is in the areas of controls measurement technology, the ability to know what happens if you crank it

up and then shut it down, and then crank it up and then shut it down. Is that the kind of additional work that needs to be done?

Dr. HARMS. That is the nature of the additional work that needs to be done in controls and measurements, yes, sir.

Mr. MACKAY. That's going to need to be done no matter which each system is decided upon.

Dr. HARMS. Yes. That's totally a generic——

Mr. MACKAY. Well, it's a state of the art that simply has not yet advanced and nobody really knows the answers, no matter what type you go with.

Dr. HARMS. But it's the kind of thing that only needs to be worked out. Again, it's not a question of feasibility.

Mr. MACKAY. But no matter what this country commits itself to it needs to know the answers if there's going to be any nuclear reactor operating in space.

Dr. HARMS. In my view; yes.

Mr. MACKAY. Do you agree with that Dr. Powell?

Dr. POWELL. Yes.

Mr. MACKAY. At what point do we have to start making final decisions as between these models?

Dr. HARMS. In my view it will depend on the definition of the mission and the so-called minimum requirements that emerge from the mission analysis. This information simply hasn't been forthcoming and I understand that it will not occur for another several months.

Mr. MACKAY. Do you have any way to measure our state of the art as contrasted to the Soviet's state of the art? Is there any way to know that?

Dr. HARMS. Based on my limited knowledge of that subject I would say we are at least even with them, and maybe ahead. But I'm not all that well informed on this issue.

Mr. MACKAY. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. MacKay.

Mr. Walker?

Mr. WALKER. Let me dwell for just a moment on a question, that Mr. MacKay just asked, which I find a little confusing. If I understand correctly, the Soviets are today operating nuclear reactors in space.

Dr. POWELL. Yes.

Mr. WALKER. At least we have had some problems with them plunging back into the atmosphere.

Why are we 10 years away from having the capability that they obviously are utilizing at the present time?

Dr. POWELL. Well, I think maybe the difference is that we want to build a higher class, or higher quality system than they are presently operating. Higher power, longer life, more capabilities, and if you have that as your goal I think it will take a while to do it.

Mr. WALKER. Well, do I understand, then, correctly, that we are capable at the present time of putting a reactor system into space which is comparable to what the Soviet's have operating?

Dr. HARMS. For the near-term, sir—that is, the early to mid-nineties—we are, indeed, in a position to do that; but not any sooner.

Mrs. LLOYD. Will the gentleman yield at that point?

Mr. WALKER. Yes.

Mrs. LLOYD. The answer might be that the funding for this program was terminated in 1973 and has not been funded at a sufficient level. We certainly are moving on this effort in this Congress.

Mr. WALKER. I thank Madam Chairman for that clarification and I think that's a very good point. What I'm getting at is, if we're talking about the 1990's before we would be capable of doing what the Soviets are doing today we're still talking 7 years.

Dr. HARMS. I think it's a question of just what exactly the Soviets are doing today. It may be—and I'm not, as I said, that well versed in this subject—that we can do certain things with solar cells and those kind of devices for applications that don't need nuclear power.

Mr. WALKER. Well, what I'm getting down to is we've been presented here with a lot of technical problems that have to be overcome in order to operate a reactor in outer space, very significant problems obviously. The Soviets are evidently doing it right now. They've evidently overcome some of those technical problems because they're operating, they're powering satellites with reactors.

In addition, they're not only doing it now but they have been doing it for some period of time. What my question really gets down to is, how is it that they have overcome all these technical problems and, regardless of the range of power of their reactors, they've overcome all these technical problems and are operating out there right now and we are still talking about the 1990's until we get there?

Mr. MACKAY. Will the gentleman yield?

Mr. WALKER. I'll be glad to yield to the gentleman.

Mr. MACKAY. Just strictly from the written testimony I understand that we flew a nuclear reactor in the midsixties which operated at levels comparable to what the Soviet's are doing now.

Dr. HARMS. The SNAP-10A system; yes.

Mr. MACKAY. So we did that and then we decided, or we exceeded our institutional memory span and we forgot what we were doing so we quit, as I understand it. Now we're going back and wondering if perhaps we should have kept on.

Mr. HARMS. You will recall that on the first chart I used, sir, SNAP-10A and the SNAP-2 and SNAP-8 systems that go with it are on the very low side of the performance level scale. Now, that level of performance we can achieve and indeed, have achieved. The Soviet's have not shown us up in the higher performance level devices at all. They would have the same problems, that we have at this stage in achieving the desired high-performance levels.

Mr. WALKER. So we don't believe that the Soviets have a reactor that they have flown which is any more sophisticated than what we flew in the sixties, is that what I understand?

Dr. HARMS. I'm not expert in this field, but it's my understanding that that's probably close to the truth.

Mr. WALKER. Now, that gets me to where I had hoped I was going. Given that, why did they choose to stick with obviously an unsophisticated system which is no better 20 years later than where we were in the sixties, and we chose not to move ahead with nuclear reactors and instead chose to go with other kinds of power systems? There was obviously a reason for that determination at

the time, a reason for their determination. Do we know why each of us chose to go different courses?

Dr. HARMS. My response to that, sir, is that your guess would be as good as mine. I really don't know why they would have the number of reactors of the low power and performance level that they have when solar panels and cells would do just as well. I don't have the answer.

Mr. WALKER. Obviously, you all have been working in the field. Why did we choose to go the different direction?

Dr. POWELL. I would assume that reactors for them were easier than solar panels, but that doesn't mean that they would have been easier for us.

Mr. WALKER. Well, is that the testimony, that from our standpoint, in the sixties, we chose solar panels as being a more viable form of power?

Dr. POWELL. For the very low power range; yes.

Mr. WALKER. And we, at that point, determined that we were never going to need any high power so we decided not to go with it?

Dr. HARMS. I would like to point out, sir, that these questions are beyond my range of expertise and the purview of my institution and the department that I represent.

Mr. WALKER. OK. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Walker. Thank you distinguished gentlemen. We will be submitting questions in writing for the record and hope that you will respond to them.

Dr. POWELL. Thank you.

Dr. HARMS. Thank you.

Mrs. LLOYD. Our next panel includes Robert Anderson, program development manager, Rockwell International; Dr. W. Howard Arnold, Westinghouse Electric Corp.; and Dr. Allen J. Rosenberg, who is vice president and general manager, Space Systems Division, General Electric. Dr. Rosenberg is accompanied by Dr. Bertram Wolfe who is also with General Electric, Nuclear Fuel and Special Projects Division. We also have with us Dr. Richard Dahlberg, director of space nuclear power, GA Technologies, Inc.

We are happy to have you gentlemen with us today. We do have your written testimony. You may summarize or proceed as you wish. Your complete statement will be made a part of the record.

Mr. Anderson, I believe you're first on our panel. We welcome you and you may proceed.

STATEMENT BY ROBERT V. ANDERSON, PROGRAM DEVELOPMENT MANAGER, ADVANCED SYSTEMS, ROCKWELL INTERNATIONAL, ENERGY SYSTEMS GROUP

Mr. ANDERSON. Madam Chairman and members of the joint subcommittee, I am Bob Anderson, of the energy systems group of Rockwell International. I am the group's program development manager for advanced systems.

As you know, Rockwell is deeply involved in and dedicated to many of this country's high technologies, especially space and space transportation, energy-generating equipment, and military aircraft. My group, the energy arm of Rockwell, is actively engaged

in essentially all of the energy-generating equipment areas—nuclear, fossil, and renewable. Our involvement in the nuclear area dates back to the early fifties with the founding of the Atomics International Division of our energy systems group. AI was a pioneer in two broad areas of nuclear technology—reactor power space applications and commercial nuclear power. I am pleased to be here today to discuss space reactor electric systems—an area that we pioneered 30 years ago.

This pioneering effort was performed on the systems for nuclear auxiliary power program—the SNAP program. Atomics International was responsible for the SNAP-2, SNAP-3, SNAP-10A, and advanced SNAP systems. To put the size of this program in perspective, the nation invested almost $300 million in these AI technologies—this would be over 1 billion 1983 dollars. As part of this effort, we worked with the Atomic Energy Commission and the Air Force to design, build, test, and flight qualify the only reactor electric system ever launched by the free world—the SNAP-10A. This system was orbited in April 1965 from Vandenberg Air Force Base and provided 500 watts of electric power to its accompanying Agena spacecraft.

We wish we could tell you that the SNAP program continued from the sixties through the eighties and that many more reactor systems were developed and launched. However, spacecraft power demands high enough to require reactors were not being projected in the early seventies and so this country's strong space reactor effort was essentially terminated at that time.

We are, however, pleased to tell you that the technology legacy—the people, the ideas, the data—was not lost. Today's renewed military and civilian interest in higher power for space has caused a rebirth of activities in the Government, at national laboratories, and at industrial contractors. As part of these activities, Rockwell completed two studies for the Department of Energy early this year. These studies assessed technologies for space reactor electric systems, and then projected the potential technologies of the future and highlighted the critical technical issues to be faced. The studies produced important insights into the capabilities of future systems. The reports from the studies received wide circulation in Government and industry.

From these studies and our involvement in the past and emerging space reactor programs, Rockwell has a solid information base and welcomes your inquiries on space reactor technologies and their potentials. We understand your key question to be: What has the United States done and how does that work apply to future space reactor systems? Another key question quite naturally follows and concerns funding: Is the funding for today's program sufficient to accomplish the goals of the program?

It is a little more enlightening to address the question on funding and goals first, and then show how the technology legacy is tied to these goals. To do this, certain comments are necessary to clarify what is meant by the goals of the program. This is best done by looking at the Nation's need for space power in the past and comparing this to what we think the need will be in the future.

Past power requirements in space were relatively low and hence did not require reactor electric systems. But this situation is chang-

ing. Power levels required by actual and near-term proposed missions have been trending upward. And although power levels for future U.S. military and civilian space missions are not yet fully defined, it is becoming apparent that much higher power levels will be needed in the future. This is true regardless of whether we speak of military or civilian missions.

Whether these needs are in the tens of kilowatt, hundreds of kilowatt, or megawatt range is yet to be determined. But no matter what results evolve from this determination, space reactor electric systems can competitively provide the needed power.

Once high power becomes available in space, more and more uses for this power—uses as yet unconceived—will be envisaged by civilian and military planners. Space reactor systems are the enabling technology for high power in space. Combined with the space transportation system and future space vehicles, reactor electric systems can become our workhorse in space.

So, the goals of the program are to determine where and when to reintroduce this reactor power capability into our space effort. The where and when will be defined by a user statement of mission needs. These mission needs must be coordinated with—and importantly, iterated against—the technology capabilities of reactor power systems. Neither activity—mission needs definition or technology capability assessment—can be performed in a vacuum. Both must proceed—with constant interaction—to define what needs to be done in light of what can be done. Only in this way will this critical enabling technology—reactor electric systems—be properly reintroduced into our space effort.

To insure that this enabling technology is properly reintroduced, today's program must determine the path—the technology roadmap—from today to the future. This technology roadmap is a plan that must be based on an understanding of the past, must include the realities of the present, and must incorporate the potential needs of the future. It is the bridge between what was done and what will be done.

We believe that this bridge is being put in place by the current program—the SP-100 program. This program has the goals of determining where and when to reintroduce reactor power systems into our space effort. The answers to the where and when are being addressed by a cooperative triagency organization. Program funding is being used to investigate both mission needs and technology capabilities in order to identify and then address the critical technical issues. At present, the funding appears sufficient to accomplish the goals.

With the funding question addressed, I can return to the question on past technologies. These past technologies—the space reactor work done in the fifties, sixties, and early seventies—form a technology legacy. The technology roadmap will start from this technology legacy. At the time the legacy evolved, Government and industry worked cooperatively to develop space reactor systems for electric power and for propulsion. As I mentioned earlier, SNAP was the program oriented toward developing electric power.

The principal SNAP reactor power systems were SNAP-2, SNAP-8, SNAP-10A, SNAP-50, and advanced SNAP. Only one of these systems—the SNAP-10A—was fabricated and flight quali-

fied. Four SNAP-10A systems were produced by Atomics International, and one was launched and operated in a 3,500-year orbit. The SNAP-10A produced one-half of 1 kilowatt of electric power, and the system was ground tested for 1 year.

The SNAP-10A system and its components were subjected to a rigorous aerospace safety program. This program—conducted by Atomics International—provided the safety technology base that permitted the first and only U.S. launch of a reactor system. Today, this is the reference technology for safety planning.

Of the remaining systems, the SNAP-2 and SNAP-8 progressed through significant development. Major components of these systems were built and tested. Two SNAP-2 reactors and two SNAP-8 reactors were full-power ground tested at Rockwell's Southern California Field Laboratories; each test lasted about 1 year. Dynamic power converting equipment—using rotating machinery—was ground tested in a simulated space environment for 1 year, as you heard Dr. Slone say. These major components of the SNAP-2 and SNAP-8 space reactor electric systems would have produced up to 50 kilowatts of electric power in space for a period of 1 year.

At the time of their development, these systems were considered very advanced. They were, in fact, ahead of their time with regard to mission needs. Other systems, such as the SNAP-50 and the advanced SNAP concepts, were on the drawing boards. These were even more advanced, using the earlier SNAP technologies as a base to achieve higher powers and longer lifetimes.

Today, where is the technology base from these programs? Some of the technology was transferred to terrestrial nuclear reactor programs throughout the United States. And now the space reactor electric system program can draw on that technology—technology from the liquid-metal fast breeder reactor and high-temperature gas-cooled reactor bases, to name a few.

But the real technology legacy lies in the people resource and in the ideas and techniques that were developed in the SNAP program. Much of this resource is still available. For example, Rockwell employs over 150 personnel with 1,100 man-years of SNAP technical experience. This resource must be combined with new capabilities and other current technologies.

The technology legacy of the past is a beginning—but it is not the entire answer for the future. That answer must evolve from thorough studies of mission needs and the mix of technologies to best satisfy those needs. However, we cannot forget the key lessons learned from the past.

One. Real mission needs are the key in the proper development of a space reactor system.

Two. A well understood sequence of technology development steps must be performed to design, develop, and flight qualify a space reactor system.

Three. A reactor system can be safely launched into space in a nonradioactive condition and then started in space upon command.

We would now like to summarize our testimony:

First. What has the United States done and how does that work apply to future space reactor systems?

The United States in the fifties, sixties, and early seventies, embarked on an ambitious program to develop space reactor electric

systems. The high point of that program was the launch and in-orbit operation of a 500-watt system, the SNAP-10A.

Other systems—the SNAP-2 and SNAP-8—were designed and reactors were built and tested, with hundreds of thousands of hours accumulated on key components.

The technology legacy of the SNAP programs—the data base, the system's engineering approach, the program management approach, and the safety program—will form the departure point and foundation for a new space reactor program. The most important legacy—the people and the lessons learned—are available now. Perhaps a little dusty and frayed around the edges—but available. The point is—we did it once, and we can do it again.

Second. Is the funding for today's program sufficient to accomplish the goals of the program?

The goals are where and when to reintroduce space reactor systems into our military and civilian space effort. These goals—the where and the when—are established by mission needs. But the needs cannot be established in a vacuum—they must take account of what technology can produce.

The current SP-100 program has wisely recognized this interplay—first by organizing around a cooperative triagency plan, and second by approaching both the mission needs and the technology potentials issues. What is being done now is to prudently decide what those needs will be in light of the technology extrapolations that can be accomplished.

We know that technology development must be performed and feel confident that the activities of the SP-100 program will provide the direction that the technology roadmap must take. The funding planned into this program appears sufficient to perform this technology roadmap activity over the planned 3-year timeframe.

However, we must caution the joint subcommittee that once a decision has been reached to proceed with reactor electric system development, significantly larger funding requirements will be necessary to achieve system launch capabilities in the early nineties. We believe the needed levels of funding are best determined in the SP-100 program. Rockwell will continue to be available to support the program in the development of the technology readmap and in the determination of the funding.

On behalf of Rockwell, I want to thank the subcommittees for the opportunity to participate in this hearing on a very important issue—an issue that will have far reaching implications for our nation in the years ahead.

[The prepared statement of Mr. Anderson, plus an addendum from Rockwell International follow:]

STATEMENT OF ROBERT V. ANDERSON*

BEFORE THE

U.S. HOUSE OF REPRESENTATIVES

COMMITTEE ON SCIENCE AND TECHNOLOGY

JOINT SUBCOMMITTEE HEARING

SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

SUBCOMMITTEE ON SPACE, SCIENCE, AND APPLICATIONS

24 MAY 1983

*PROGRAM DEVELOPMENT MANAGER, ADVANCED SYSTEMS
ENERGY SYSTEMS GROUP
ROCKWELL INTERNATIONAL

CONGRESSIONAL TESTIMONY

MADAM CHAIRMAN AND MEMBERS OF THE JOINT SUBCOMMITTEE, I AM BOB ANDERSON, OF THE ENERGY SYSTEMS GROUP OF ROCKWELL INTERNATIONAL. I AM THE GROUP'S PROGRAM DEVELOPMENT MANAGER FOR ADVANCED SYSTEMS.

AS YOU KNOW, ROCKWELL IS DEEPLY INVOLVED IN AND DEDICATED TO MANY OF THIS COUNTRY'S HIGH TECHNOLOGIES, ESPECIALLY SPACE AND SPACE TRANSPORTATION, ENERGY-GENERATING EQUIPMENT, AND MILITARY AIRCRAFT. MY GROUP, THE ENERGY ARM OF ROCKWELL, IS ACTIVELY ENGAGED IN ESSENTIALLY ALL OF THE ENERGY-GENERATING EQUIPMENT AREAS — NUCLEAR, FOSSIL, AND RENEWABLE. OUR INVOLVEMENT IN THE NUCLEAR AREA DATES BACK TO THE EARLY 1950S WITH THE FOUNDING OF THE ATOMICS INTERNATIONAL DIVISION OF OUR ENERGY SYSTEMS GROUP. AI WAS A PIONEER IN TWO BROAD AREAS OF NUCLEAR TECHNOLOGY — REACTOR POWER FOR SPACE APPLICATIONS AND COMMERCIAL NUCLEAR POWER. I AM PLEASED TO BE HERE TODAY TO DISCUSS SPACE REACTOR ELECTRIC SYSTEMS — AN AREA THAT WE PIONEERED 30 YEARS AGO.

22-828 O—83——6

THIS PIONEERING EFFORT WAS PERFORMED ON THE SYSTEMS FOR NUCLEAR AUXILIARY POWER PROGRAM – THE SNAP PROGRAM. ATOMICS INTERNATIONAL WAS RESPONSIBLE FOR THE SNAP-2, SNAP-8, SNAP-10A, AND ADVANCED SNAP SYSTEMS. TO PUT THE SIZE OF THIS PROGRAM IN PERSPECTIVE, THE NATION INVESTED ALMOST 300 MILLION DOLLARS IN THESE AI TECHNOLOGIES (THIS WOULD BE OVER ONE BILLION 1983 DOLLARS). AS PART OF THIS EFFORT, WE WORKED WITH THE ATOMIC ENERGY COMMISSION AND THE AIR FORCE TO DESIGN, BUILD, TEST, AND FLIGHT QUALIFY THE ONLY REACTOR ELECTRIC SYSTEM EVER LAUNCHED BY THE FREE WORLD – THE SNAP-10A. THIS SYSTEM WAS ORBITED IN APRIL 1965 FROM VANDENBERG AIR FORCE BASE AND PROVIDED 500 W OF ELECTRIC POWER TO ITS ACCOMPANYING AGENA SPACECRAFT.

WE WISH WE COULD TELL YOU THAT THE SNAP PROGRAM CONTINUED FROM THE 1960S THROUGH THE 1980S AND THAT MANY MORE REACTOR SYSTEMS WERE DEVELOPED AND LAUNCHED. HOWEVER, SPACECRAFT POWER DEMANDS HIGH ENOUGH TO REQUIRE REACTORS WERE NOT BEING PROJECTED IN THE EARLY 1970S, AND SO THIS COUNTRY'S STRONG SPACE REACTOR EFFORT WAS ESSENTIALLY TERMINATED AT THAT TIME.

WE ARE, HOWEVER, PLEASED TO TELL YOU THAT THE TECHNOLOGY LEGACY – THE PEOPLE, THE IDEAS, THE DATA – WAS NOT LOST. TODAY'S RENEWED MILITARY AND CIVILIAN INTEREST IN HIGHER POWER FOR SPACE HAS CAUSED A REBIRTH OF ACTIVITIES IN THE GOVERNMENT, AT NATIONAL LABORATORIES, AND AT INDUSTRIAL CONTRACTORS. AS PART OF THESE ACTIVITIES, ROCKWELL COMPLETED TWO STUDIES FOR THE DEPARTMENT OF ENERGY EARLY THIS YEAR. THESE STUDIES ASSESSED TECHNOLOGIES FOR SPACE REACTOR ELECTRIC SYSTEMS, AND THEN PROJECTED THE POTENTIAL TECHNOLOGIES OF THE FUTURE AND HIGHLIGHTED THE CRITICAL TECHNICAL ISSUES TO BE FACED. THE STUDIES PRODUCED IMPORTANT INSIGHTS INTO THE CAPABILITIES OF FUTURE SYSTEMS. THE REPORTS FROM THE STUDIES RECEIVED WIDE CIRCULATION IN GOVERNMENT AND INDUSTRY.

FROM THESE STUDIES AND OUR INVOLVEMENT IN THE PAST AND EMERGING SPACE REACTOR PROGRAMS, ROCKWELL HAS A SOLID INFORMATION BASE AND WELCOMES YOUR INQUIRIES ON SPACE REACTOR TECHNOLOGIES AND THEIR POTENTIALS. WE UNDERSTAND YOUR KEY QUESTION TO BE: WHAT HAS THE U.S. DONE AND HOW DOES THAT WORK APPLY TO FUTURE SPACE REACTOR SYSTEMS? ANOTHER KEY QUESTION QUITE NATURALLY FOLLOWS AND CONCERNS FUNDING: IS THE FUNDING FOR TODAY'S PROGRAM SUFFICIENT TO ACCOMPLISH THE GOALS OF THE PROGRAM?

IT IS MORE ENLIGHTENING TO ADDRESS THE QUESTION ON FUNDING AND GOALS FIRST, AND THEN SHOW HOW THE TECHNOLOGY LEGACY IS TIED TO THESE GOALS. TO DO THIS, CERTAIN COMMENTS ARE NECESSARY TO CLARIFY WHAT IS MEANT BY ". . . THE GOALS OF THE PROGRAM." THIS IS BEST DONE BY LOOKING AT THE NATION'S NEED FOR SPACE POWER IN THE PAST AND COMPARING THIS TO WHAT WE THINK THE NEED WILL BE IN THE FUTURE.

PAST POWER REQUIREMENTS IN SPACE WERE RELATIVELY LOW AND HENCE DID NOT REQUIRE REACTOR ELECTRIC SYSTEMS. BUT THIS SITUATION IS CHANGING. POWER LEVELS REQUIRED BY ACTUAL AND NEAR-TERM PROPOSED MISSIONS HAVE BEEN TRENDING UPWARD. AND ALTHOUGH POWER LEVELS FOR FUTURE U.S. MILITARY AND CIVILIAN SPACE MISSIONS ARE NOT YET FULLY DEFINED, IT IS BECOMING APPARENT THAT MUCH HIGHER POWER LEVELS WILL BE NEEDED IN THE FUTURE. THIS IS TRUE REGARDLESS OF WHETHER WE SPEAK OF MILITARY OR CIVILIAN MISSIONS.

WHETHER THESE NEEDS ARE IN THE TENS OF KILOWATT, HUNDREDS OF KILOWATT, OR MEGAWATT RANGE IS YET TO BE DETERMINED. BUT NO MATTER WHAT RESULTS EVOLVE FROM THIS DETERMINATION, SPACE REACTOR ELECTRIC SYSTEMS CAN COMPETITIVELY PROVIDE THE NEEDED POWER.

ONCE HIGH POWER BECOMES AVAILABLE IN SPACE, MORE AND MORE USES FOR THIS POWER — USES AS YET UNCONCEIVED — WILL BE ENVISAGED BY CIVILIAN AND MILITARY PLANNERS. SPACE REACTOR SYSTEMS ARE THE ENABLING TECHNOLOGY FOR HIGH POWER IN SPACE. COMBINED WITH THE SPACE TRANSPORTATION SYSTEM AND FUTURE SPACE VEHICLES, REACTOR ELECTRIC SYSTEMS CAN BECOME OUR WORKHORSE IN SPACE.

THE GOALS OF THE PROGRAM ARE THUS TO DETERMINE WHERE AND WHEN TO REINTRODUCE THIS REACTOR POWER CAPABILITY INTO OUR SPACE EFFORT. THE WHERE AND WHEN WILL BE DEFINED BY A USER STATEMENT OF MISSION NEEDS. THESE MISSION NEEDS MUST BE COORDINATED WITH — AND ITERATED AGAINST — THE TECHNOLOGY CAPABILITIES OF REACTOR POWER SYSTEMS. NEITHER ACTIVITY — MISSION NEEDS DEFINITION OR TECHNOLOGY CAPABILITY ASSESSMENT — CAN BE PERFORMED IN A VACUUM. BOTH MUST PROCEED — WITH CONSTANT INTERACTION — TO DEFINE WHAT NEEDS TO BE DONE IN LIGHT OF WHAT CAN BE DONE. ONLY IN THIS WAY WILL THIS CRITICAL ENABLING TECHNOLOGY — REACTOR ELECTRIC SYSTEMS — BE PROPERLY REINTRODUCED INTO OUR SPACE EFFORT.

TO ENSURE THAT THIS ENABLING TECHNOLOGY IS PROPERLY REINTRODUCED, TODAY'S PROGRAM MUST DETERMINE THE PATH – THE TECHNOLOGY ROADMAP – FROM TODAY TO THE FUTURE. THIS TECHNOLOGY ROADMAP IS A PLAN THAT MUST BE BASED ON AN UNDERSTANDING OF THE PAST, MUST INCLUDE THE REALITIES OF THE PRESENT, AND MUST INCORPORATE THE POTENTIAL NEEDS OF THE FUTURE. IT IS THE BRIDGE BETWEEN WHAT WAS DONE AND WHAT WILL BE DONE.

WE BELIEVE THAT THIS BRIDGE IS BEING PUT IN PLACE BY THE CURRENT PROGRAM – THE SP-100 PROGRAM. THIS PROGRAM HAS THE GOALS OF DETERMINING WHERE AND WHEN TO REINTRODUCE REACTOR POWER SYSTEMS INTO OUR SPACE EFFORT. THE ANSWERS TO THE WHERE AND WHEN ARE BEING ADDRESSED BY A COOPERATIVE TRI-AGENCY ORGANIZATION. PROGRAM FUNDING IS BEING USED TO INVESTIGATE BOTH MISSION NEEDS AND TECHNOLOGY CAPABILITIES IN ORDER TO IDENTIFY AND THEN ADDRESS THE CRITICAL TECHNICAL ISSUES. AT PRESENT, THE FUNDING APPEARS SUFFICIENT TO ACCOMPLISH THE GOALS.

WITH THE FUNDING QUESTION ADDRESSED, I CAN RETURN TO THE QUESTION ON PAST TECHNOLOGIES. THESE PAST TECHNOLOGIES – THE SPACE REACTOR WORK DONE IN THE 1950s, 1960s, AND EARLY 1970s – FORM A TECHNOLOGY LEGACY. THE TECHNOLOGY ROADMAP WILL START FROM THIS TECHNOLOGY LEGACY. AT THE TIME THE LEGACY EVOLVED, GOVERNMENT AND INDUSTRY WORKED COOPERATIVELY TO DEVELOP SPACE REACTOR SYSTEMS FOR ELECTRIC POWER AND FOR PROPULSION. AS I MENTIONED EARLIER, SNAP WAS THE PROGRAM ORIENTED TOWARD DEVELOPING ELECTRIC POWER.

THE PRINCIPAL SNAP REACTOR POWER SYSTEMS WERE SNAP-2, SNAP-8, SNAP-10A, SNAP-50, AND ADVANCED SNAP. ONLY ONE OF THESE SYSTEMS – THE SNAP-10A – WAS FABRICATED AND FLIGHT QUALIFIED. FOUR SNAP-10A SYSTEMS WERE PRODUCED BY ATOMICS INTERNATIONAL, AND ONE WAS LAUNCHED AND OPERATED IN A 3500-YEAR ORBIT. THE SNAP-10A PRODUCED 1/2 OF 1 KILOWATT OF ELECTRIC POWER, AND THE SYSTEM WAS GROUND TESTED FOR 1 YEAR.

THE SNAP-10A SYSTEM AND ITS COMPONENTS WERE SUBJECTED TO A RIGOROUS AEROSPACE SAFETY PROGRAM. THIS PROGRAM – CONDUCTED BY ATOMICS INTERNATIONAL – PROVIDED THE SAFETY TECHNOLOGY BASE THAT PERMITTED THE FIRST AND ONLY U.S. LAUNCH OF A REACTOR SYSTEM. TODAY, THIS IS THE REFERENCE TECHNOLOGY FOR SAFETY PLANNING.

Of the remaining systems, the SNAP-2 and SNAP-8 progressed through significant development. Major components of these systems were built and tested. Two SNAP-2 reactors and two SNAP-8 reactors were full-power ground tested at Rockwell's Southern California Field Laboratories; each test lasted about one year. Dynamic power converting equipment — using rotating machinery — was ground tested in a simulated space environment for one year. These major components of the SNAP-2 and SNAP-8 space reactor electric systems would have produced up to 50 kW of electric power in space for a period of one year.

At the time of their development, these systems were considered very advanced. They were, in fact, "ahead of their time" with regard to misson needs. Other systems, such as the SNAP-50 and the Advanced SNAP concepts, were on the drawing boards. These were even more advanced, using the earlier SNAP technologies as a base to achieve higher powers and longer lifetimes.

TODAY, WHERE IS THE TECHNOLOGY BASE FROM THESE PROGRAMS? SOME OF THE TECHNOLOGY WAS TRANSFERRED TO TERRESTRIAL NUCLEAR REACTOR PROGRAMS THROUGHOUT THE U.S. AND NOW THE SPACE REACTOR ELECTRIC SYSTEM PROGRAM CAN DRAW ON THAT TECHNOLOGY — TECHNOLOGY FROM THE LIQUID-METAL FAST BREEDER REACTOR AND HIGH-TEMPERATURE GAS-COOLED REACTOR BASES, TO NAME A FEW.

BUT THE REAL TECHNOLOGY LEGACY LIES IN THE PEOPLE RESOURCE AND IN THE IDEAS AND TECHNIQUES THAT WERE DEVELOPED IN THE SNAP PROGRAM. MUCH OF THIS RESOURCE IS STILL AVAILABLE. FOR EXAMPLE, ROCKWELL EMPLOYS OVER 150 PERSONNEL WITH 1100 MAN-YEARS OF SNAP TECHNICAL EXPERIENCE. THIS RESOURCE MUST BE COMBINED WITH NEW CAPABILITIES AND OTHER CURRENT TECHNOLOGIES.

THE TECHNOLOGY LEGACY OF THE PAST IS A BEGINNING — BUT IT IS NOT THE ENTIRE ANSWER FOR THE FUTURE. THAT ANSWER MUST EVOLVE FROM THOROUGH STUDIES OF MISSION NEEDS AND THE MIX OF TECHNOLOGIES TO BEST SATISFY THOSE NEEDS. HOWEVER, WE CANNOT FORGET THE KEY LESSONS LEARNED FROM THE PAST:

1. REAL MISSION NEEDS ARE THE KEY IN THE PROPER DEVELOPMENT OF A SPACE REACTOR SYSTEM.

2. A WELL UNDERSTOOD SEQUENCE OF TECHNOLOGY DEVELOPMENT STEPS MUST BE PERFORMED TO DESIGN, DEVELOP, AND FLIGHT QUALIFY A SPACE REACTOR SYSTEM.

3. A REACTOR SYSTEM CAN BE SAFELY LAUNCHED INTO SPACE IN A NONRADIOACTIVE CONDITION AND THEN STARTED IN SPACE UPON COMMAND.

WE WOULD NOW LIKE TO SUMMARIZE OUR TESTIMONY:

FIRST: WHAT HAS THE U.S. DONE AND HOW DOES THAT WORK APPLY TO FUTURE SPACE REACTOR SYSTEMS?

THE U.S., IN THE 1950s, 1960s, AND EARLY 1970s, EMBARKED ON AN AMBITIOUS PROGRAM TO DEVELOP SPACE REACTOR ELECTRIC SYSTEMS. THE HIGH POINT OF THAT PROGRAM WAS THE LAUNCH AND IN-ORBIT OPERATION OF A 500-W SYSTEM, THE SNAP-10A.

OTHER SYSTEMS – THE SNAP-2 AND SNAP-8 – WERE DESIGNED AND REACTORS WERE BUILT AND TESTED, WITH HUNDREDS OF THOUSANDS OF HOURS ACCUMULATED ON KEY COMPONENTS.

THE TECHNOLOGY LEGACY OF THE SNAP PROGRAMS – THE DATA BASE, THE SYSTEM'S ENGINEERING APPROACH, THE PROGRAM MANAGEMENT APPROACH, AND THE SAFETY PROGRAM – WILL FORM THE DEPARTURE POINT AND FOUNDATION FOR A NEW SPACE REACTOR PROGRAM. THE MOST IMPORTANT LEGACY – THE PEOPLE AND THE LESSONS LEARNED – ARE AVAILABLE NOW. PERHAPS A LITTLE DUSTY AND FRAYED AROUND THE EDGES – BUT AVAILABLE. THE POINT IS – WE DID IT ONCE, AND WE CAN DO IT AGAIN.

SECOND IS THE FUNDING FOR TODAY'S PROGRAM SUFFICIENT TO ACCOMPLISH THE GOALS OF THE PROGRAM?

THE GOALS ARE WHERE AND WHEN TO REINTRODUCE SPACE REACTOR SYSTEMS INTO OUR MILITARY AND CIVILIAN SPACE EFFORT. THESE GOALS – THE WHERE AND THE WHEN – ARE ESTABLISHED BY MISSION NEEDS. BUT THE NEEDS CANNOT BE ESTABLISHED IN A VACUUM – THEY MUST TAKE ACCOUNT OF WHAT TECHNOLOGY CAN PRODUCE.

THE CURRENT SP-100 PROGRAM HAS WISELY RECOGNIZED THIS INTERPLAY — FIRST BY ORGANIZING AROUND A COOPERATIVE TRI-AGENCY PLAN, AND SECOND BY APPROACHING BOTH THE MISSION NEEDS AND THE TECHNOLOGY POTENTIALS ISSUES. WHAT IS BEING DONE NOW IS TO PRUDENTLY DECIDE WHAT THOSE NEEDS WILL BE IN LIGHT OF THE TECHNOLOGY EXTRAPOLATIONS THAT CAN BE ACCOMPLISHED.

WE KNOW THAT TECHNOLOGY DEVELOPMENT MUST BE PERFORMED AND FEEL CONFIDENT THAT THE ACTIVITIES OF THE SP-100 PROGRAM WILL PROVIDE THE DIRECTION THAT THE TECHNOLOGY ROADMAP MUST TAKE. THE FUNDING PLANNED INTO THIS PROGRAM APPEARS SUFFICIENT TO PERFORM THIS TECHNOLOGY ROADMAP ACTIVITY OVER THE PLANNED 3-YEAR TIME FRAME.

HOWEVER, WE MUST CAUTION THE JOINT SUBCOMMITTEE THAT ONCE A DECISION HAS BEEN REACHED TO PROCEED WITH REACTOR ELECTRIC SYSTEM DEVELOPMENT, SIGNIFICANTLY LARGER FUNDING REQUIREMENTS WILL BE NECESSARY TO ACHIEVE SYSTEM LAUNCH CAPABILITIES IN THE EARLY 1990S. WE BELIEVE THE NEEDED LEVELS OF FUNDING ARE BEST DETERMINED IN THE SP-100 PROGRAM. ROCKWELL WILL CONTINUE TO BE AVAILABLE TO SUPPORT THE PROGRAM IN THE DEVELOPMENT OF THE TECHNOLOGY ROADMAP AND IN THE DETERMINATION OF THE FUNDING.

ON BEHALF OF ROCKWELL, I WANT TO THANK THE JOINT SUBCOMMITTEE FOR THE OPPORTUNITY TO PARTICIPATE IN THIS HEARING ON A VERY IMPORTANT ISSUE — AN ISSUE THAT WILL HAVE FAR REACHING IMPLICATIONS FOR OUR NATION IN THE YEARS AHEAD.

Biography

Robert V. Anderson
Program Development Manager, Advanced Systems
Energy Systems Group
Rockwell International

Robert V. Anderson, of Rockwell's Energy Systems Group, directs the company's activities to develop advanced energy systems.

The Energy Systems Group encompasses five business divisions and is engaged in a broad range of energy programs, including nuclear, fossil, and renewable. The Group's advanced energy system efforts draw heavily on the technology base at both the Group and at other Rockwell organizations. In the space nuclear energy area, this base includes the SNAP technology from the Group's Atomics International Division and the aerospace technologies from Rockwell's space organizations.

Mr. Anderson joined Rockwell's Atomics International Division in 1970 as a nuclear analyst for the SNAP-8 Developmental Reactor and advanced SNAP systems. He soon advanced and became responsible for SNAP systems analysis. In the mid-1970s, he was project manager for Component Development, and was responsible for the successful transfer of NASA's advanced turbopump technology to DOE's LMFBR components program. In May 1980, he was promoted to his present position as program development manager of Advanced Systems. In this position, he managed DOE's most recent studies on space reactor systems and participated in the National Research Council's November 1982 Symposium on Advanced Compact Reactor Systems.

Mr. Anderson received his B.S. in engineering physics from the University of California, Berkeley, in 1968. He earned his M.S. in nuclear engineering in 1970, also from U.C. Berkeley, where he was an AEC Special Fellow in Nuclear Science and Engineering. Mr. Anderson, a registered nuclear engineer in California, is a member of the AIAA Aerospace Power Systems Committee and of Phi Beta Kappa.

THE U.S. SPACE REACTOR PROGRAM

- THE PAST
- THE PRESENT
- THE FUTURE

TESTIMONY ADDENDUM
U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE AND TECHNOLOGY

24 MAY 1983

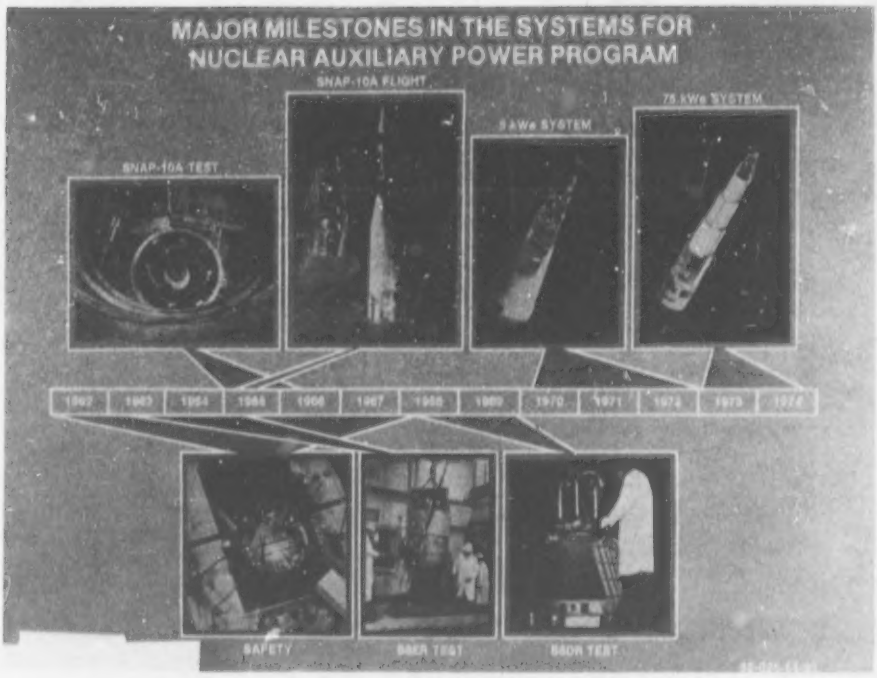
THE PAST

History of the Systems for Nuclear Auxiliary Power
(SNAP) Program at Rockwell International
and
Its legacy to the present

- Eighteen years ago, on April 3, 1965, the U.S. successfully launched the first space nuclear reactor system – the SNAP-10A – into orbit from Vandenberg AFB.
- That system – in producing nearly 500 kW-hr of energy during its 1000 hr of operation – conclusively demonstrated the validity of the concept of space reactor electric power systems.

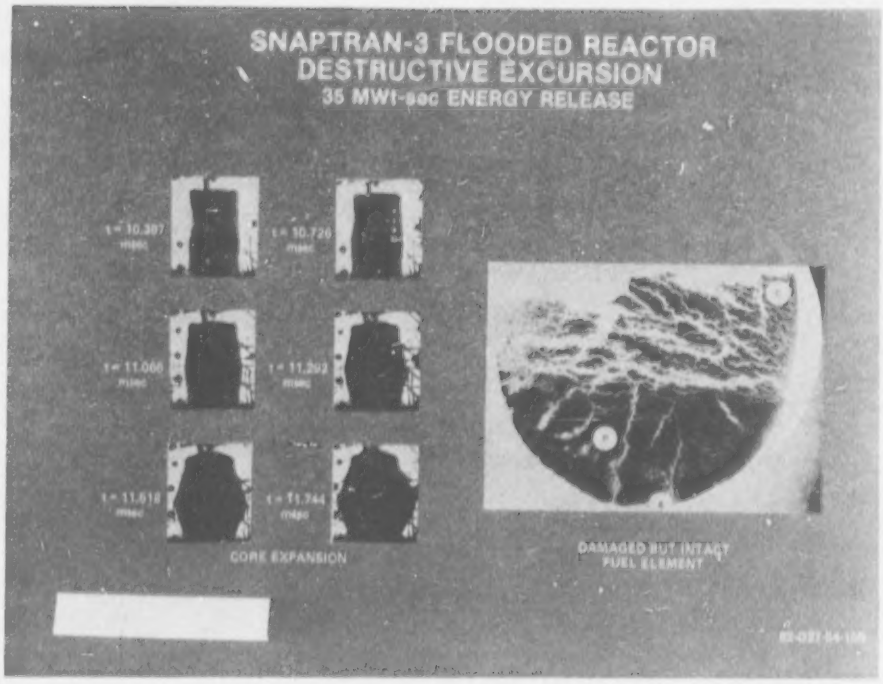
The SNAP-10A launch and its operation in-orbit was the high point of nearly 20 years of intensive effort at Rockwell's Atomics International Division on the design, development, and testing of space reactors and space reactor electric systems.

That 20-year Rockwell effort – from the early 1950s through the early 1970s – saw the testing of six reactors for an accumulated 41,250 hours and the testing of components for literally hundreds of thousands of hours.



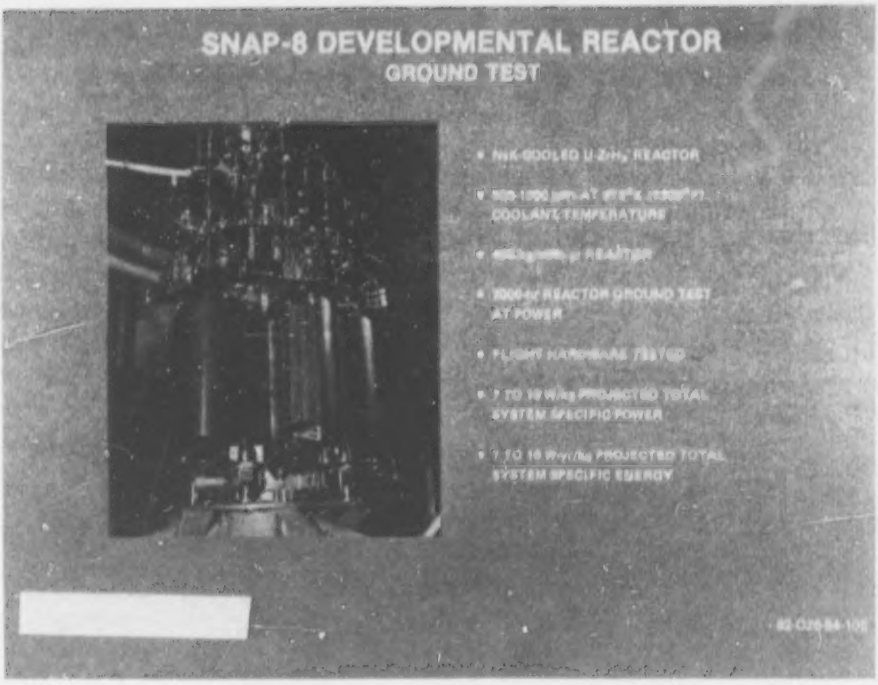
An extensive aerospace safety program was conducted by Rockwell. The safety program answered questions relating to the consequences of launch abort, intact reentry, water flooding of the reactor, and other potential accident conditions.

Tests included an actual reentry test (using a simulated, nonnuclear reactor mockup), a full-scale destructive reactor test (known as the SNAPTRAN test series), plus numerous other tests necessary to assure that the safety consequences of accident conditions were acceptable.



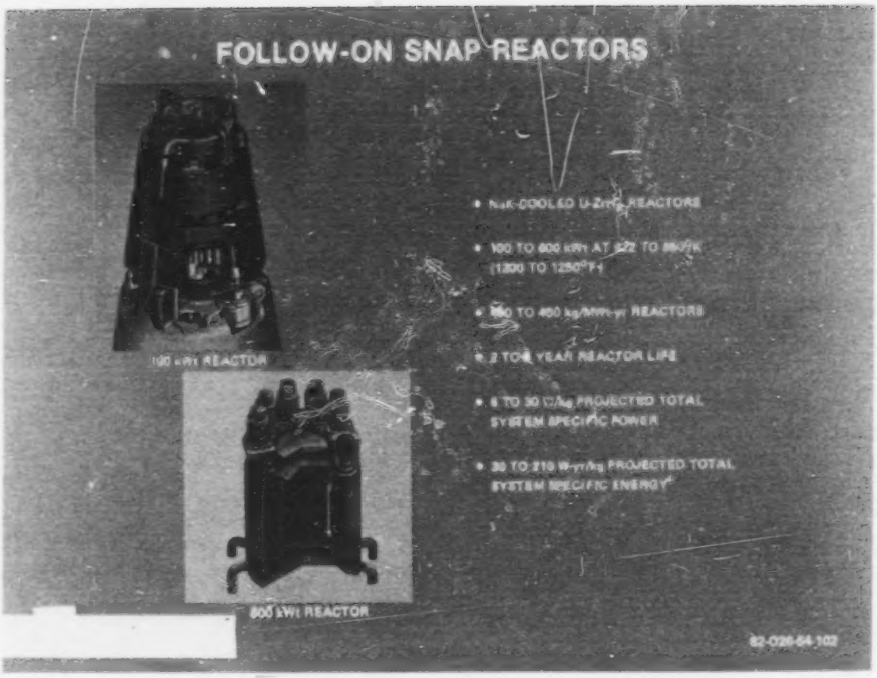
The SNAP-8 space reactor electric system was designed to produce up to 50 kWe using a mercury-driven turbine developed by Aerojet General.

Two SNAP-8 reactors were designed, built, and tested by Rockwell for a total of 17,000 hr before the SNAP Program was terminated in the early 1970s.


SNAP-8 DEVELOPMENTAL REACTOR
GROUND TEST
• NaK-COOLED U-ZrH REACTOR
COOLANT TEMPERATURE
• 1000-hr REACTOR GROUND TEST AT POWER
• PROJECTED TOTAL SYSTEM SPECIFIC POWER
• PROJECTED TOTAL SYSTEM SPECIFIC ENERGY

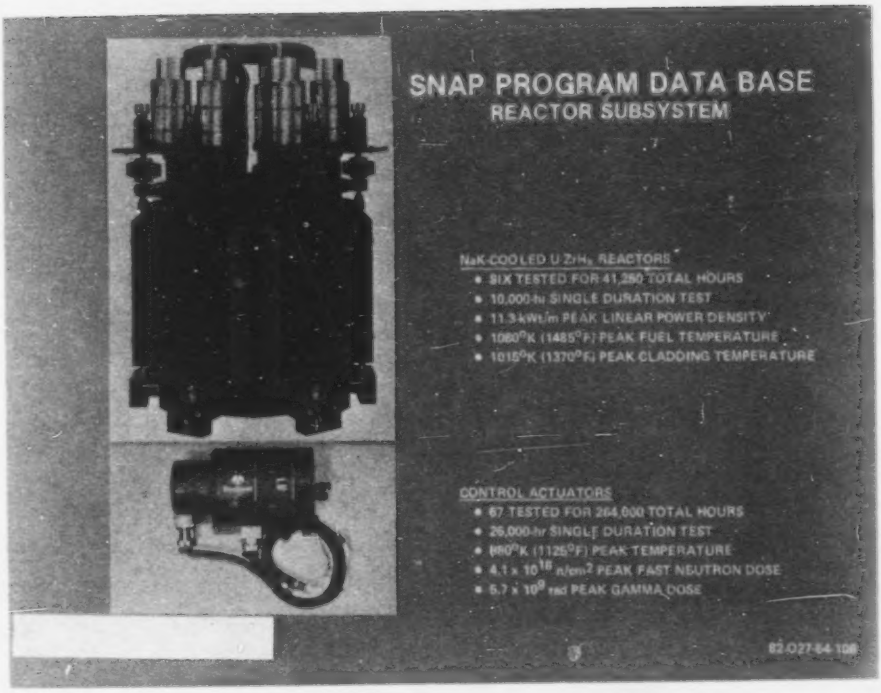
In the early 1970s, several advanced space reactor electric systems were studied by Rockwell. Power levels ranged from 5 to 75 kWe.

In 1973, the SNAP reactor program was terminated due to the lack of an identified mission. But the program left a technology legacy for future space reactor electric systems.



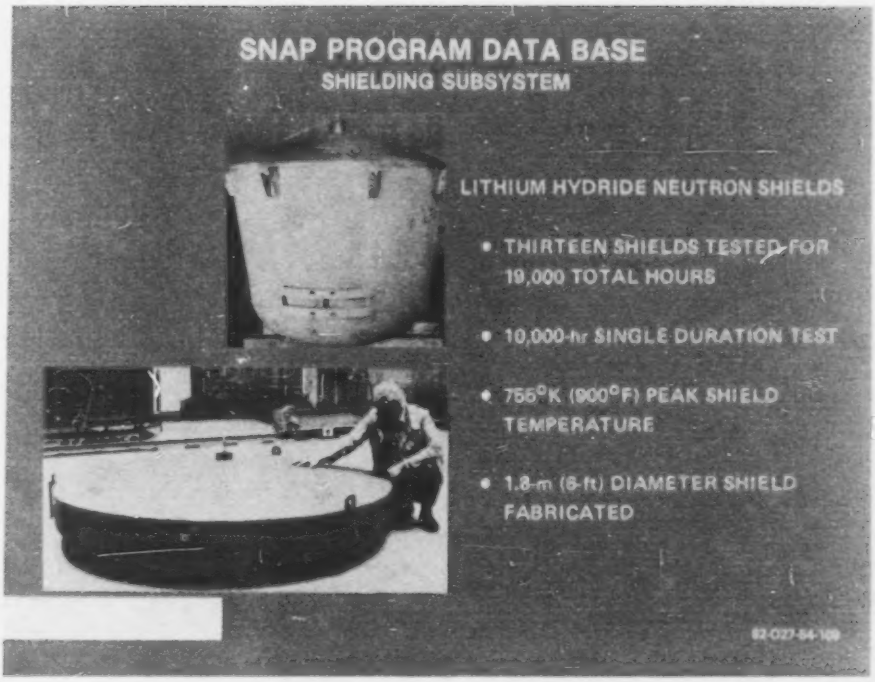
THE SNAP TECHNOLOGY LEGACY

- For the reactor subsystem


SNAP PROGRAM DATA BASE
REACTOR SUBSYSTEM
NaK-COOLED U ZrH$_x$ REACTORS
• SIX TESTED FOR 41,280 TOTAL HOURS
• 10,000-hr SINGLE DURATION TEST
• 11.3 kWt/in PEAK LINEAR POWER DENSITY
• 1080°K (1485°F) PEAK FUEL TEMPERATURE
• 1018°K (1370°F) PEAK CLADDING TEMPERATURE
CONTROL ACTUATORS
• 67 TESTED FOR 264,000 TOTAL HOURS
• 26,000-hr SINGLE DURATION TEST
• 880°K (1125°F) PEAK TEMPERATURE
• 4.1 x 10^{18} n/cm^2 PEAK FAST NEUTRON DOSE
• 5.7 x 10^9 rad PEAK GAMMA DOSE
82-027-64-108

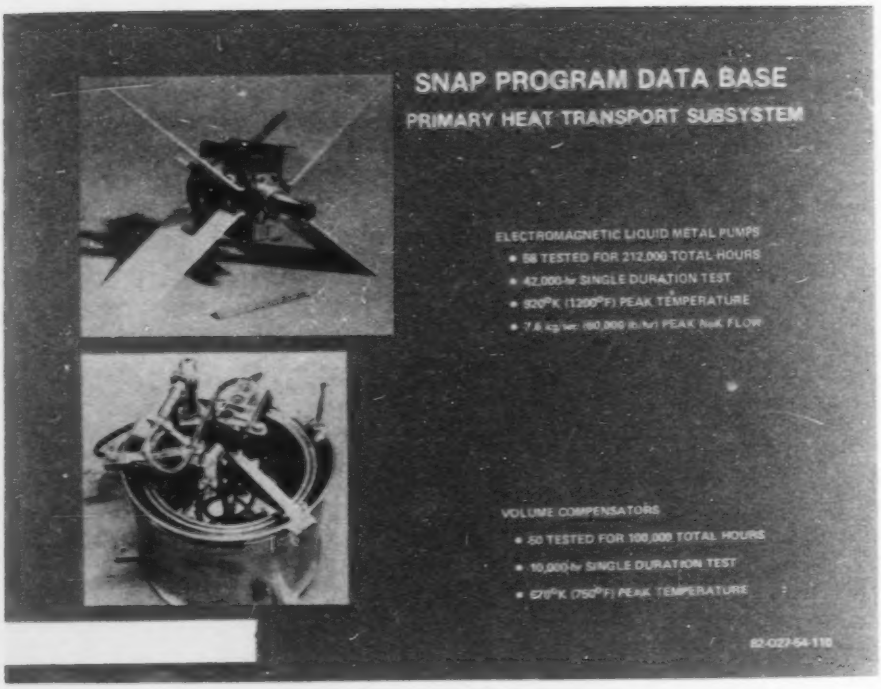
THE SNAP TECHNOLOGY LEGACY

- For the shielding subsystem


SNAP PROGRAM DATA BASE
SHIELDING SUBSYSTEM
LITHIUM HYDRIDE NEUTRON SHIELDS
• THIRTEEN SHIELDS TESTED FOR 19,000 TOTAL HOURS
• 10,000-hr SINGLE DURATION TEST
• 755°K (900°F) PEAK SHIELD TEMPERATURE
• 1.8-m (6-ft) DIAMETER SHIELD FABRICATED
82-027-64-109

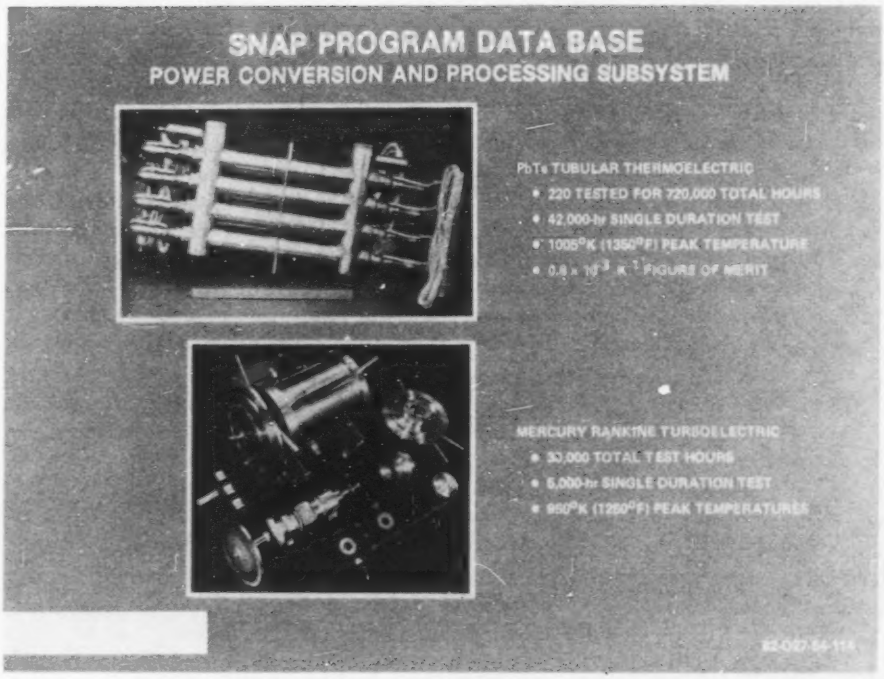
THE SNAP TECHNOLOGY LEGACY

- For the primary heat transport subsystem


SNAP PROGRAM DATA BASE
PRIMARY HEAT TRANSPORT SUBSYSTEM
ELECTROMAGNETIC LIQUID METAL PUMPS
• 58 TESTED FOR 212,000 TOTAL HOURS
• 42,000-hr SINGLE DURATION TEST
• 920°K (1200°F) PEAK TEMPERATURE
• 7.6 kg/sec (60,000 lb/hr) PEAK NaK FLOW
VOLUME COMPENSATORS
• 50 TESTED FOR 100,000 TOTAL HOURS
• 10,000-hr SINGLE DURATION TEST
• 672°K (750°F) PEAK TEMPERATURE
62-027-54-110

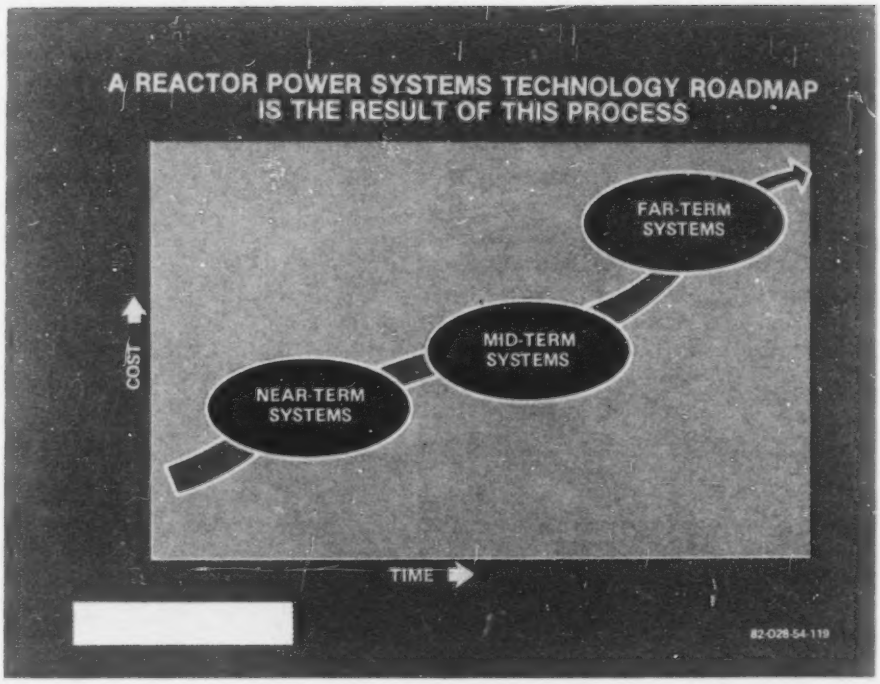
THE SNAP TECHNOLOGY LEGACY

- For the power conversion subsystem

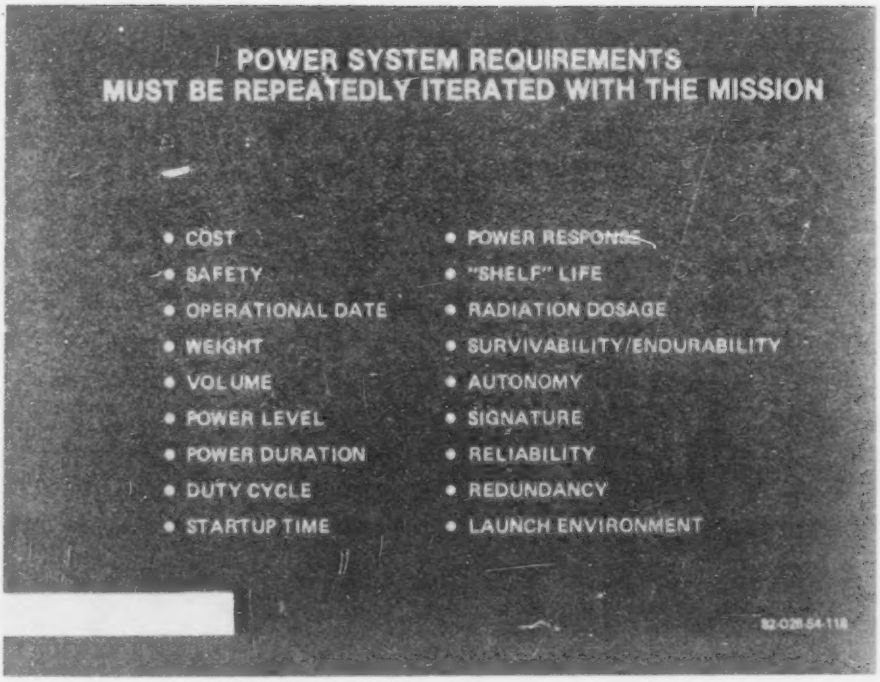

SNAP PROGRAM DATA BASE
POWER CONVERSION AND PROCESSING SUBSYSTEM
PbTe TUBULAR THERMOELECTRIC
• 220 TESTED FOR 720,000 TOTAL HOURS
• 42,000-hr SINGLE DURATION TEST
• 1005°K (1350°F) PEAK TEMPERATURE
• 0.8 x 10⁻³ K⁻¹ FIGURE OF MERIT
MERCURY RANKINE TURBOELECTRIC
• 30,000 TOTAL TEST HOURS
• 5,000-hr SINGLE DURATION TEST
• 950°K (1250°F) PEAK TEMPERATURES

THE PRESENT

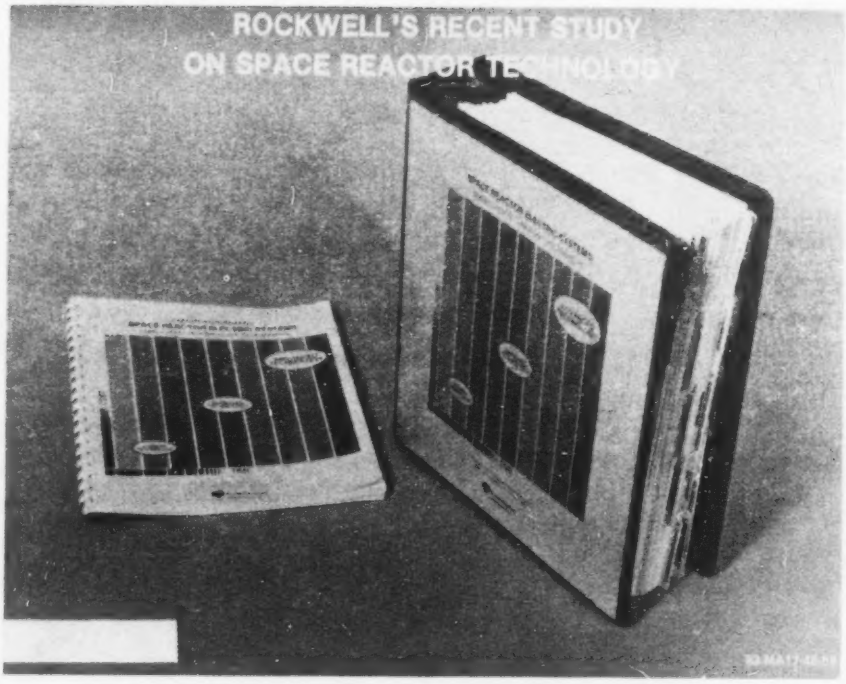
The technology legacy is the starting point for the development of future space reactor electric systems.



The SP-100 Program is currently establishing power system requirements by iterating power system technology capabilities against mission needs. A key decision point will occur in 1985, when the future technical direction and program schedule will be established based on the results of this iterative process.

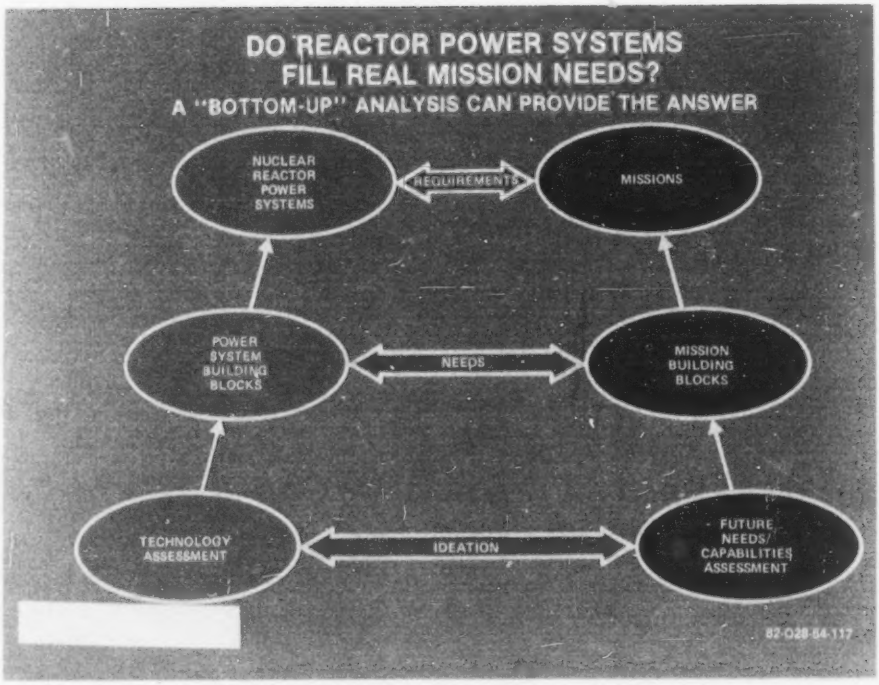


Rockwell recently completed a study for DOE that assessed all major technologies for Space Reactor Electric Systems. This is the first step in assembling a "bottom-up" analysis for addressing mission needs versus technology capabilities.

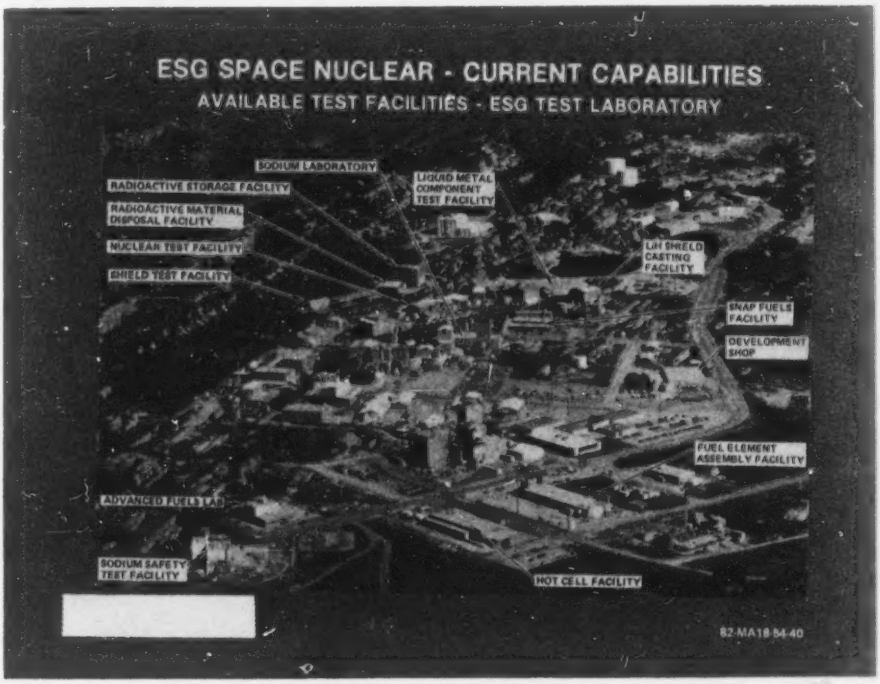


THE FUTURE

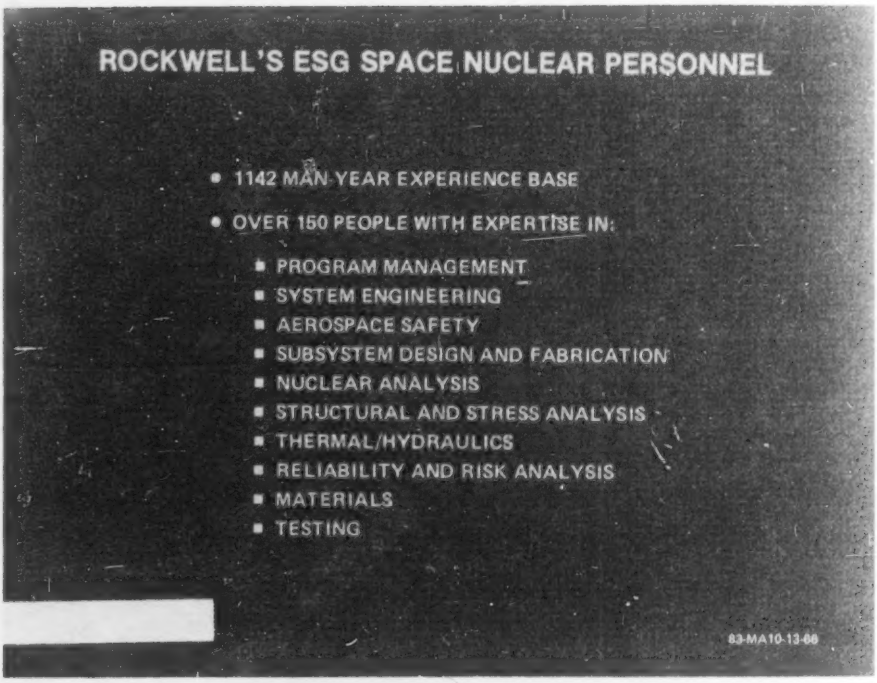
The shape of things to come will depend on mission needs now being addressed by the SP-100 Program. Space reactor electric systems will need to respond to the challenges presented by these mission needs.



Rockwell's study report (ESG-DOE-13398) is a factbook of past and current technology for the subsystems that make up a space reactor electric system. Copies of this report were sent to the staff of the Subcommittee on Energy Research and Production.

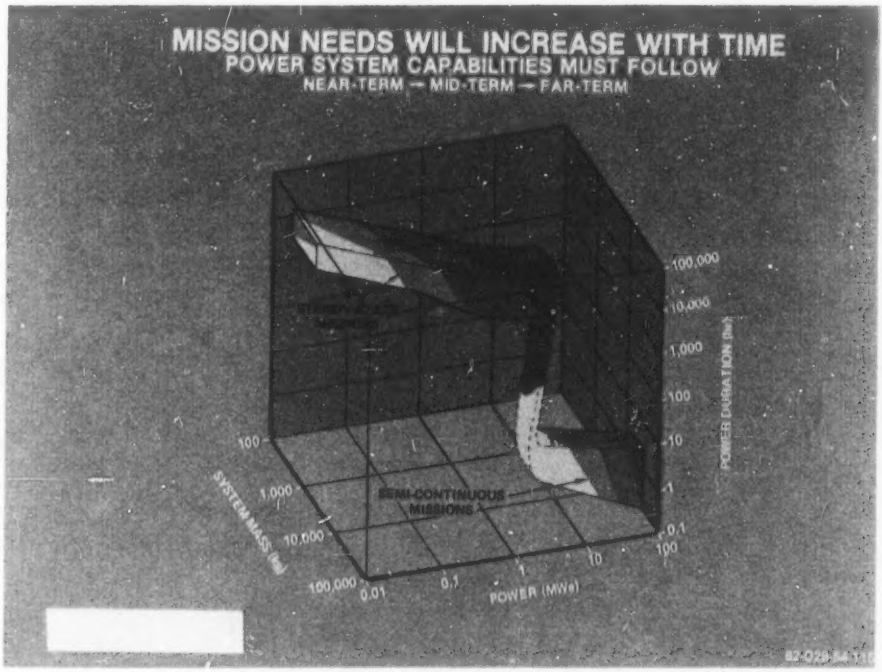


The Shuttle has ushered in a new era in space. It is clear from the current interest and activity in the space frontier that space nuclear power is no longer a concept ahead of its time.

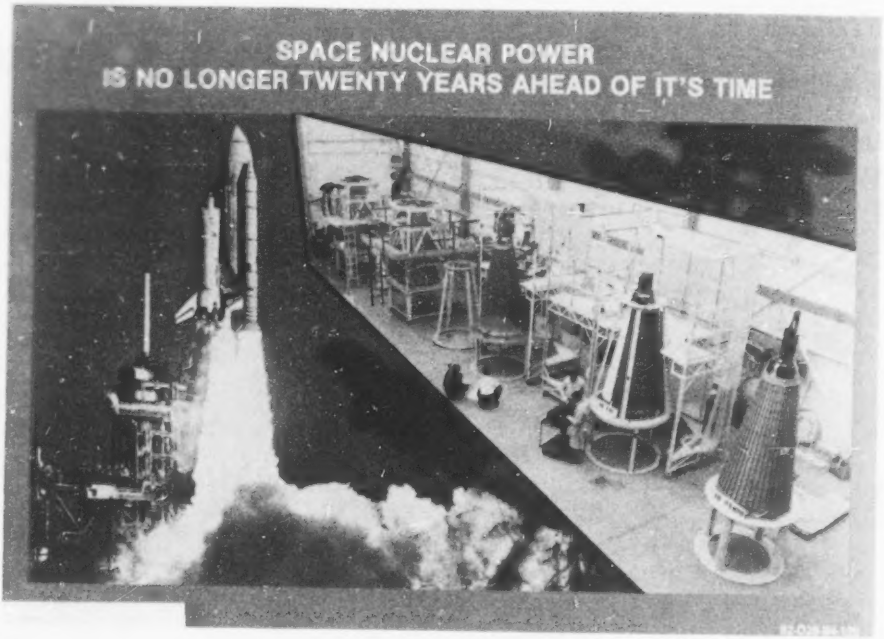


Many of the test facilities used in support of the SNAP Program still exist at Rockwell's Field Test Laboratory, located in the Santa Susana mountains just west of ESG's Canoga Park, California headquarters.

These people and facilities are available to meet our nations future space challenges.



Rockwell is proud of its past and present role in meeting the nation's needs for space reactor electric systems. Despite the decade of relative inactivity, Rockwell's Energy Systems Group has maintained a significant contingent of highly experienced technical personnel.


SPACE NUCLEAR POWER
IS NO LONGER TWENTY YEARS AHEAD OF IT'S TIME

Mrs. LLOYD. Thank you, Mr. Anderson.
Dr. Arnold, you may proceed.

STATEMENT BY DR. W. HOWARD ARNOLD, GENERAL MANAGER, ADVANCED REACTORS DIVISION, WESTINGHOUSE ELECTRIC CORP.

Dr. ARNOLD. Madam Chairman and members of the subcommittee, my name is Howard Arnold. I am general manager of the Westinghouse Advanced Energy Systems Division, which is headquartered in Madison, Pa., but has a substantial operation in Oak Ridge, Tenn. Our technical staff and facilities are dedicated to the development of new energy technologies for future commercial and Government applications. Energy technologies currently being pursued by Westinghouse AESD include solar, fuel cell, and MHD systems, but our major thrust has been directed toward advanced nuclear power systems for space and terrestrial applications. This emphasis is a logical outgrowth of the successful pioneering efforts of Westinghouse in naval propulsion reactors and commercial nuclear powerplants as well as our past lead role in development of the NERVA gas-cooled space propulsion reactor and currently on the liquid-metal-cooled fast breeder reactor, particularly the fast flux test facility and Clinch River breeder reactor. We have in Westinghouse at least 200 professional people who are experienced in both of these programs—the space program and the liquid-metal reactor program.

In recent years Westinghouse AESD has conducted internally funded studies which have applied these advanced reactor technologies to the conceptual design of compact, lightweight space nuclear powerplants. We are currently participating in Government-funded studies on the feasibility of 100-kilowatt class space nuclear power systems. I welcome the opportunity to share my views on the status and potential of space nuclear power technology.

I have been personally involved in significant technical and management positions in pressurized water reactors, liquid-metal reactors, and the NERVA nuclear rocket reactor. Accordingly, my views represent an industry perspective derived from an extensive base of related technical and project-management experience which I hope will prove useful in your deliberations.

I will eliminate some of the testimony as I understand you are pressed for time.

Mrs. LLOYD. Your complete testimony will be made a part of the record, Dr. Arnold.

Dr. ARNOLD. The ongoing SP–100 program funded by DOD, DOE, and NASA to evaluate the feasibility of advanced space nuclear power systems is a prudent first step toward insuring that future space missions of vital national interest will not be jeopardized by constraints on power system output.

In detailing the program to develop such a system, I see four key program issues to be addressed: What is the mission? How can the health and safety of the world's people be assured? What critical technologies must be addressed immediately? What ground test facilities will be required?

Clearly, definition of a leading candidate mission early in the program is critical because a detailed program plan required to guide program development and demonstration activities cannot be prepared without specifications on mission-oriented parameters such as power level, duty cycle, lifetime, reliability and so forth. Furthermore, a well-defined mission provides the necessary focus for galvanizing program support for real schedules and adequate funding.

Protection of public health and safety must be assured during all phases of space power missions, particularly for short-lived orbit missions when disposition of the radioactive core must be accomplished in conformance with U.S. and international standards on public radiation exposure. The public will demand such assurances for, first, the reactor in its preoperational state; second, sufficient isolation and longevity of its orbital operational state; and, third, inherent safety due to burnup in the event of reentry. It will also be necessary to demonstrate in advance an acceptable low level of risk during the development and ground test phases of the program. We performed a substantial development program of this nature during the NERVA program, and are convinced that no insuperable technological problems exist in this area.

The technical challenges involved in developing and deploying a space nuclear power system in the 100-kilowatt class are substantial but an extensive base of related technology and experience exists to justify confidence that such a task is indeed feasible. The NERVA nuclear rocket program of the sixties used sophisticated analytical methods and test facilities to produce a proven lightweight gas-cooled reactor design which can be readily adapted to a space power application. In addition, the ongoing LMFBR program has carried liquid-metal-cooled fast reactor technology to an advanced development status. These two reactor-design options, gas and liquid metal, not only promise low programmatic risks associated with proven technologies, but also provide a valuable opportunity to minimize development costs at a time when Federal R&D funds are limited. Other concepts have been proposed with attractive features for a space power mission but must be carefully evaluated in terms of R&D requirements and technical risk. We have recently performed a preliminary evaluation of all these concepts as candidates for a megawatt-class system and concluded that some are amenable to substantially higher power ratings by reasonable design and modifications. The selection and development of a design concept which can be extrapolated to a megawatt-class capability represents a potentially major cost-reduction measure which should be considered. In addition, the successful ground testing of 18 reactors in the ROVER NERVA series gives us confidence in an overall development schedule measured in years rather than in decades. In spite of this extensive technology base, the viability of advanced space power system concepts will require advances in technology areas which are critical to program success and which must be addressed early in the program. In particular, every reactor program successfully pursued in the past has required the development and qualification of some key materials, and this one will be no exception. Such materials include those used in the fuel,

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the structural material and the power conversion and safety systems.

Following selection of the most promising candidate concept, it is our judgment that the development of an advanced space power system should proceed with the design of a system which is appropriate for ground testing, yet readily adaptable to a flight-rated configuration. To maximize the success potential of a ground-test program and to minimize the number of costly ground-test articles, a development and qualification program for key components and subsystems should be substantially completed before an integrated system test is attempted. The fact that the test article is a power reactor system will require special facilities for remote operation, maintenance, disassembly and post-test examination. These facilities will most likely pace the overall program so that it is imperative to get an early start. Parenthetically, I think I would interpose that this probably is the answer to Mr. Walker's question—that's there is a necessary infrastructure for a program like this that is not now fully in place. Pieces of it are left from old programs but it is not now there in an integrated way.

The types of facilities needed include reactor-test complexes and assembly/disassembly facilities capable of handling highly radioactive reactor materials. Fortunately, some of these capabilities exist from prior programs.

I would like to show a few slides, if I may, showing some of the facilities and test articles from the previous NERVA program.

Slide No. 1. That's a NERVA reactor ready for a critical experiment at our facility in Waltz Mill, Pa. This was taken in the middle 1960's.

Slide No. 2. This is a NERVA reactor ontest at the Nevada test site. This was a 1 hour test run. That was a thousand-megawatt thermal reactor.

Slide No. 3. This is the NERVA XE-engine in its stand prior to test. It was successfully tested through 28 start and restart cycles.

Slide No. 4. This is an external view of a facility which is now used for characterization of means of storing reactor fuel assemblies, but in those days it was called the Engine Maintenance Assembly and Disassembly Facility. It was built specifically for the disassembly of a NERVA engine after it had been fired. That's again in the Nevada test site.

Slide No. 5. The next one is a view inside that facility. What it is is a very large hot cell, capable of being remotely operated from the outside, not with people in it as it shows now.

Slide No. 6. Finally, just to show another part of the program. This is a picture of the FFTF [Fast Flux Test Facility] in Hanford, Wash. I show this because I think the liquid-metal reactor technology in that reactor, which is now successfully operating, is also applicable. The building in the front is the nearly completed Fuel Material Examination Facility in which an integrated fuel cycle capability is to be prepared in coming years.

In summary, anticipated U.S. space power needs for the 1990's and the inherent sophistication of nuclear fission technology justify continued, if not expanded, congressional support of the emerging triagency program for development of a 100-kilowatt class space nuclear power system. Demonstrated reactor and power conversion

technologies can be adapted to such a mission and provide a high degree of confidence that such a system is not only feasible but can be developed within a reasonable cost and schedule.

Westinghouse is very proud of its record in assisting the U.S. Government in many successful nuclear and defense programs, including naval propulsion, nuclear rockets, and reactors for production of electric power. We would be very pleased to be a major contributor to this next vital step.

[The prepared statement of Dr. Arnold, plus a report on "Technology Status and Development Requirements for Advanced Space Nuclear Power Systems," follow:]

TESTIMONY OF DR. W. HOWARD ARNOLD

WESTINGHOUSE ELECTRIC CORPORATION

BEFORE THE SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

COMMITTEE ON SCIENCE AND TECHNOLOGY

U. S. HOUSE OF REPRESENTATIVES

MAY 24, 1983

Madame Chairwoman and Members of the Subcommittee, my name is Dr. Howard Arnold. I am General Manager of the Westinghouse Advanced Energy Systems Division (AESD), whose technical staff and facilities are dedicated to the development of new energy technologies for future commercial and government applications. Energy technologies currently being pursued by Westinghouse AESD include solar, fuel cell and MHD systems, but our major thrust has been directed towards advanced nuclear power systems for space and terrestrial applications. This emphasis is a logical outgrowth of the successful pioneering efforts of Westinghouse in naval propulsion reactors and commercial nuclear power plants as well as our past lead role in development of the NERVA gas-cooled space propulsion reactor and currently on the liquid-metal-cooled fast breeder reactor, particularly FFTF and CRBR.

In recent years, AESD has conducted internally funded studies which have applied these advanced reactor technologies to the conceptual design of compact, light-weight space nuclear power plants. We are currently participating in government-funded studies on the feasibility of one-hundred-kilowatt-class space nuclear power systems. I welcome the opportunity to share my views on the status and potential of space nuclear power technology.

I have been personally involved in significant technical and management positions in pressurized water reactors, liquid metal reactors, and the NERVA nuclear rocket reactor. Accordingly, my views represent an industry perspective derived from an extensive base of related technical and project-management experience which I hope will prove useful in your deliberations.

Current requirements for space power systems based on mission needs and technology status are modest (1-2 kWe) and have been met by a variety of technologies including chemical systems, solar arrays with batteries, fuel cells, and radioisotope-thermoelectric generators. Although civilian and military space missions being considered for deployment during the next decade and beyond are not yet fully defined, it is apparent that the higher electrical power ranges required by increasingly sophisticated spacecraft and payloads will be achievable only by using compact, high-specific-power systems such as a fission-reactor heat source. The ongoing SP-100 program funded by DOD, DOE and NASA to evaluate the feasibility of advanced space nuclear power systems is a prudent first-step towards ensuring that future space missions of vital national interest will not be jeopardized by constraints on power system output.

In detailing the program to develop such a system, I see four key program issues to be addressed:

- What is the mission?
- How can the health and safety of the world's people be assured?
- What critical technologies must be addressed immediately?
- What ground test facilities will be required?

Space power systems in the hundred-kilowatt and megawatt classes are being considered for low-earth-orbit (LEO) and deep-space missions, involving operational lifetimes in the range of 5-10 years. Such missions will impose unique and stringent requirements on system performance, safety, reliability, technology development and spacecraft integration. For example, constraints on power system size and mass arising from the limited payload capabilities of available launch vehicles will have a major influence on the system concept eventually selected for deployment. The high power density and compact size achievable with fast and intermediate spectrum reactors are features which must be fully exploited in order to satisfy these physical constraints. Recent Westinghouse studies on 100 kWe space power systems indicate that a complex trade-off between design options will be involved in selecting a power conversion subsystem with performance and reliability characteristics which satisfy mission requirements. Clearly, definition of a leading candidate mission early in the program is critical because a detailed program plan required to guide program development and demonstration activities can not be prepared without specifications on mission-oriented parameters such as power level, duty cycle, lifetime, reliability, etc. Furthermore, a well defined mission provides the necessary focus for galvanizing program support for real schedules and adequate funding.

Protection of public health and safety must be assured during all phases of space power missions, particularly for short-lived orbit missions when disposition of the radioactive core must be accomplished in conformance with U.S. and international standards on public radiation exposure. The public will demand such assurances for (1) the reactor in its pre-operational state, (2) sufficient isolation and longevity of its orbital

operational state, and (3) inherent safety due to burn-up in the event of re-entry. It will also be necessary to demonstrate in advance an acceptable low level of risk during the development and ground test phases of the program. The atmospheric re-entry of two Russian surveillance-satellite reactors within the last five years reveals that malfunctions of space nuclear systems also have international implications and must be avoided by an appropriate system design and by a vigorous development and qualification program. We performed a substantial development program of this nature during the NERVA program, and are convinced that no insuperable technological problems exist in this area.

The technical challenges involved in developing and deploying a space nuclear power system in the one-hundred-kilowatt class are substantial but an extensive base of related technology and experience exists to justify confidence that such a task is indeed feasible. The NERVA nuclear rocket program of the 1960's used sophisticated analytical methods and test facilities to produce a proven lightweight gas-cooled reactor design which can be readily adapted to a space power application. The ongoing LMFBR program has carried liquid-metal-cooled fast reactor technology to an advanced development status. Previous Westinghouse studies on nuclear powered aircraft and space power systems indicate that the liquid-metal concept has high potential as a space power system. These two reactor-design options, gas and liquid metal, not only promise low programmatic risks associated with proven technologies, but also provide a valuable opportunity to minimize development costs at a time when federal R&D funds are limited. Other concepts have been proposed with attractive features for a space

power mission but must be carefully evaluated in terms of R&D requirements and technical risk. We have recently performed a preliminary evaluation of all these concepts as candidates for a megawatt-class system and concluded that some are amenable to substantially higher power ratings by reasonable design modifications. The selection and development of a design concept which can be extrapolated to a megawatt-class capability represents a potentially major cost-reduction measure which should be considered. In addition, the successful ground testing of eighteen reactors in the ROVER-NERVA series gives us confidence in an overall development schedule measured in years rather than decades. In spite of this extensive technology base, the viability of advanced space power system concepts will require advances in technology areas which are critical to program success and which must be addressed early in the program. In particular, every reactor program successfully pursued in the past has required the development and qualification of some key materials, and this one will be no exception. Such materials include those used in the fuel, the structural material and the power conversion and safety systems.

Following selection of the most promising candidate concept, it is our judgement that the development of an advanced space power system should proceed with the design of a system which is appropriate for ground testing, yet readily adaptable to a flight-rated configuration. To maximize the success potential of a ground-test program and to minimize the number of costly ground-test articles, a development and qualification program for key components and subsystems should be substantially completed before an integrated system test is attempted. The fact that the test article

is a power reactor system will require special facilities for remote operation, maintenance, disassembly and post-test examination. These facilities will most likely pace the overall program so that it is imperative to get an early start. The types of facilities needed include reactor-test complexes and assembly/disassembly facilities capable of handling highly radioactive reactor materials. Fortunately, some capabilities exist from prior programs such as the NERVA test facilities at the Nevada site.

In summary, anticipated U.S. space power needs for the 1990's and the inherent sophistication of nuclear fission technology justify continued, if not expanded, Congressional support of the emerging tri-agency program for development of a hundred-kilowatt-class space nuclear power system. Demonstrated reactor and power conversion technologies can be adapted to such a mission and provide a high degree of confidence that such a system is not only feasible but can be developed within a reasonable cost and schedule.

Westinghouse is very proud of its record in assisting the U.S. government in many successful nuclear and defense programs, including naval propulsion, nuclear rockets, and reactors for production of electric power. We would be very pleased to be a major contributor to this next vital step.

TECHNOLOGY STATUS AND DEVELOPMENT REQUIREMENTS FOR ADVANCED SPACE NUCLEAR POWER SYSTEMS

ADVANCED ENERGY SYSTEMS DIVISION
WESTINGHOUSE ELECTRIC CORP.
MAY 24, 1983

I. INTRODUCTION AND SUMMARY

The U.S. has made outstanding contributions to aerospace power and propulsion technology over the past 25 years, which have permitted dramatic progress in the exploration and exploitation of space for the benefit of the civilian and military sectors. The successful commissioning of the Space Shuttle and the consequential interest in deploying larger and more advanced systems have called attention to the need for timely development of advanced power supplies so that important space missions of the 1990's will not be unduly constrained by power considerations.

The combination of future space power requirements at the hundred-kilowatt level and launch-vehicle limitations on system mass and size dictate the use of a nuclear reactor heat source and an appropriate thermal/electrical converter for generation of electric power. Recent initiatives in the form of technology surveys and pre-conceptual design studies have established the applicability of the extensive technology base which exists in lightweight gas-cooled and liquid-metal-cooled reactors (derived primarily from the NERVA, SNAP and LMFBR programs) to an advanced space nuclear power system. This assessment provides a high degree of confidence that a hundred-kilowatt-class system with required performance characteristics is feasible and that a development program leading to a flight-qualified system will have an acceptable cost and schedule.

Safety considerations will have a significant impact on the design and mission profile of a space nuclear power system but related experience on the SNAP and NERVA programs indicate that implementation of established safety requirements in the SP-100 program will not pose any insuperable technological problem.

Programmatic issues which are considered important to the success of this emerging national program include the necessity of firmly establishing a mission and associated functional requirements early in the program so that system development need not be interrupted by major design changes to

accommodate revisions in performance specifications. Another such issue is the need for adequate and stable funding which a prolonged development program of this type must receive in order to maintain a cost-effective pace and a dedicated design team.

II. U.S. SPACE POWER REQUIREMENTS

Over the past two decades of space exploration and system development, launch vehicle constraints on payload size have limited electric power systems to a kilowatt or less. Demand for lower-power sources for longer-duration missions has been supplied primarily by solar and isotope systems whereas fuel cells have been used for the higher-power, shorter-duration applications. With the advent of the Space Shuttle, larger satellites with increased power requirements are being planned for future DOD (military) and NASA (civilian) space missions. Ongoing activities have been limited and have been focusing primarily on the development of promising long-lead-time technologies until specific mission and associated power requirements are defined. However, guidelines are now emerging[1,2,3] which indicate that a comprehensive mission-oriented development program for a space reactor power system can and should be initiated promptly.

A. DOD/NASA Space Missions

Military spacecraft missions in the communication, navigation and meteorological areas currently require power in the neighborhood of 1 to 2 kW. This is expected to grow moderately to 5 to 15 kW by 1990 due to on-board data processing, enhanced communication cross-linking, increased on-station housekeeping requirements and higher powered downlink transmitters to support the increased use of small and diversified ground communication facilities.

Advanced DOD missions are expected to include a category of applications requiring steady-state power in the hundred-kilowatt range, as shown in Table 1. Assuming additional growth in launch capability and further development of Command, Control, Communication and Intelligence (C^3I) mission technologies and requirements, a need can be anticipated for megawatt-class sources of continuous power, perhaps by the end of the 1990's. Table 1 also reveals that future DOD space weapons will likely require a power source that can

TABLE 1
POTENTIAL DOD SPACE POWER REQUIREMENTS (REFERENCE 4)

Application	Power Level
Space-Based Radars	5-400 kW
Surveillance	30-100 kW
Communications	100 kW
Orbit Transfer Vehicle (NEP)	100 kW
Jammers	70-200 kW
Lasers	10-100's MW pulsed
Particle Beam	10-100's MW pulsed
Advanced Concepts	1-100's MW continuous or pulsed

supply up to hundreds of megawatts in a pulsed mode.[4] Since limitations will still be imposed on payload size and weight, high-specific-power concepts which are long-lived and survivable will become increasingly attractive as these advanced DOD mission concepts mature.

Although future NASA programs to extend its space exploration and exploitation activities will be substantially fund-limited, potential missions that could be undertaken over the next several decades include operation of large satellites in geosynchronous orbit requiring electric power in the 5-200 kW range. Exploration of the outer planets using electrical propulsion would require power supplies in the 200-500 kW range.[5]

B. Advanced Power System Development

On the basis of the overview of future DOD/NASA space-power needs described above, it appears that the development of a base-load electric power system in the hundred-kilowatt class would satisfy presently identified C^3I mission requirements. Since the development time for such a system is inherently long in relation to the anticipated 1990's need-date, a program for the development of an advanced high-power source of electricity should begin promptly.

Since funding will also be limited for DOD missions, the design concept selected for the hundred-kilowatt class system should preferably be based upon technologies which can be extrapolated to the megawatt class. Systems with this higher power rating will probably be deployed beyond the 1990's and, therefore, should be developed under a parallel effort. The requirement for pulsed, multi-hundred-megawatt-class power sources for DOD space weapons clearly involves a radically different operating mode that must be pursued in a separate development program. The relative merits of nuclear and chemical technologies for this application must be further evaluated.

C. Technology Options

Technologies which can and have been used to produce power for space applications include chemical systems, solar arrays with batteries, radioisotopes and nuclear reactors. Figure 1 shows where each technology option can best perform on an electric power/mission-duration map[5]. A DOD/ERDA review[6] of these technologies revealed that for most DOD missions, involving extended time in orbit and power requirements in excess of 50 KWe, nuclear reactors are the most practical means of meeting DOD needs.

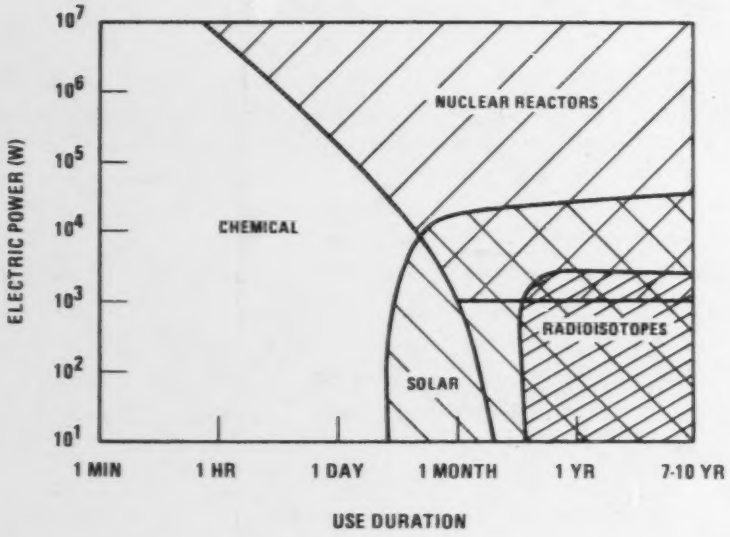

Figure 1. Applicability of Power-Technology Options to Space Mission of Various Power Requirements and Orbital Duration (Reference 5)

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III. TECHNOLOGY STATUS

Although the development of fission reactors in the U.S. for military (naval propulsion) and civilian (electric power) applications quickly focused on the less complex technology of thermal-spectrum water-cooled reactors, considerable interest and attention continued to be directed towards the characteristics and applications of alternative concepts. Substantial Research & Development (R&D) was performed on the engineering feasibility of gas-cooled and liquid-metal-cooled reactors as well as on the physics and safety characteristics of epithermal and fast-spectrum cores. The technological progress on these advanced reactor concepts was sufficiently encouraging by the mid-1950's that major R&D programs were established to apply these technologies to a variety of sophisticated missions, including aircraft engines and space power and propulsion systems.

Several gas-cooled reactor concepts were pursued with primary emphasis on propulsion applications. The U.S. nuclear rocket program (Rover), consisting of broad and comprehensive reactor design, development and ground-testing activities, carried the epithermal high-temperature hydrogen-cooled graphite reactor to a proven-design status. This was achieved in the NERVA project which operated the NRX-A6 test reactor at full temperature and power for its full design life (60 minutes) and successfully completed performance tests on a down-firing NERVA-XE ground-test engine. During the later phases of the nuclear rocket program, substantial progress was made in the development of an advanced NERVA fuel element with improved resistance to hydrogen corrosion and, accordingly, a significant increase in fuel lifetime. Development of a flight engine was ready to proceed in 1971 when the NERVA program was terminated.

Other potentially attractive thermal, epithermal and fast gas-cooled reactor concepts were investigated during this period. These were not carried beyond the engineering-design phase and, therefore, would still require extensive development and testing to achieve proven-design status.

The development of liquid-metal, convection-cooled reactors for space applications received focused attention during the 1960's. The low-temperature, thermal-spectrum SNAP-10A space power reactor utilizing a zirconium-hydride core and NaK coolant was successfully flight tested in 1965. Lithium-cooled reactors using uranium-nitride fuel for space power (e.g., SPR-6) and aircraft propulsion (e.g., NuERA II) applications were carried to the engineering design stage, with testing limited to select materials and/or components. Even though such reactors have received little attention since the early 1970's, the extensive progress that has been made to date on the development of liquid metal fast breeder reactor technology has significantly advanced the design status of liquid-metal, forced-convection cooled reactors.

More recent space-power projects have been investigating the feasibility of fast reactors cooled by conduction to in-core and out-of-core heat pipes filled with liquid metal as a working fluid. The scope of these space reactor projects has consisted to date of conceptual design studies coupled with development of critical technologies, primarily the design of long liquid-metal heat pipes. Other advanced space power systems of current interest include particle-bed reactors which are also in the conceptual design phase.

Since the most cost-effective approach to initiating the development of an advanced nuclear space power system is to maximize the use of the extensive technology base which already exists, this section describes relevant aerospace nuclear power and propulsion programs which form this technology base and in which Westinghouse played a significant role.

A. Nuclear Rocket Engine (NERVA)

Major progress in the development of lightweight, gas-cooled reactor technology was accomplished under the U.S. nuclear rocket program, which was initiated by the Los Alamos Scientific Laboratory (LASL) in 1955 and reached advanced development status[8] through the efforts of a government-industry team. This program sought to utilize the

high specific impulse of a nuclear rocket in order to circumvent the limitations of chemical systems for advanced scientific and civilian missions. The NERVA flight engine reactor was sized to provide 1500 MW thermal power for a rated engine thrust of 75,000 pounds at a specific impulse of 825 seconds. The overall engine reliability requirement was confidently set at an extremely high level; 0.995 at a 90 percent confidence level.

Based on the LASL Kiwi design, the NERVA engine utilized a hydrogen-cooled epithermal reactor containing a core of uranium-carbide fuel beads dispersed in a graphite matrix and a radial beryllium reflector with rotating neutron-absorber drums for control of reactor power, as shown in Figure 2. The nucleonics of the reactor was dominated by the large void fraction associated with the numerous coolant channels and by the niobium coatings in the channels that protected the graphite core against the highly reactive hydrogen coolant.

In addition to demonstrating the ability of the reactor to operate for an extended period at desired power and temperature levels, the NERVA program had to address a number of basic feasibility questions with regard to reactor structural integrity, restart capability and controllability.

Structural integrity and performance were demonstrated by successful operation of 15 Kiwi and NRX reactors. Early in the nuclear rocket program, serious vibrational problems were encountered in the 1962 Kiwi-B test, leaving the structural integrity of the reactors in doubt. Tests conducted in 1964 by Los Alamos Scientific Laboratory and the NERVA team proved that the difficulty was understood and had been corrected by an improved lateral support system. Confidence then increased sufficiently to increase the reactor-performance goal to 60 minutes of full-power operation, which was subsequently achieved with the NRX-A6 reactor test article.

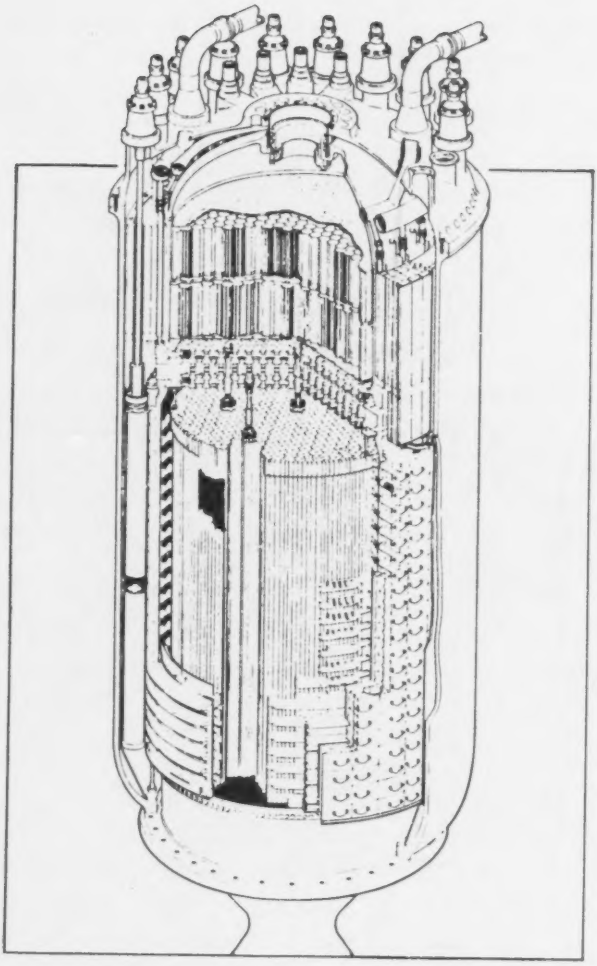

FIGURE 2 - NERVA REACTOR ASSEMBLY

In the NRX test reactors, hydrogen in liquid form entered the reflector from the regeneratively cooled thrust nozzle at a temperature on the order of -260°F. After cooling the reflector, pressure vessel, control drum actuators, internal shield and the support plate, the hydrogen entered the core at approximately -230°F. Most of the hydrogen passed through the fuel element channels wherein it was heated to approximately 4000°F. A fraction of the core hydrogen flow was used to cool the tie rods after which it was mixed with the fuel channel exit gas to provide nominal nozzle chamber conditions of 550 psia and 3630°F.

More than 25 reactor startups, including many restarts, were successfully accomplished in the Kiwi/NRX test series. In addition, 10 reactor startups to power conditions were successfully executed in the first complete engine system test (NRX/EST). These tests conclusively demonstrated the restartability and reusability of the NERVA nuclear system.

Other reactor tests resolved the questions about controllability of the system associated with the nuclear reactivity effects of the hydrogen coolant under the extremes of temperature, flow, and start-times dictated by a nuclear rocket.

Tests then shifted from reactor-related experiments to the performance of a ground-test engine called the NERVA-XE, successfully completed in September 1969, which were conducted with the engine firing downward into a simulated space environment, as shown in Figure 3. The steps included multiple restarts, throttling and automatic control startup by use of "bootstrap" techniques. The engine was started 28 times and was operated at various thrust levels for a cumulative time of 3 hours and 48 minutes, which included some time at full power of 1100 MW and thrust of 55,000 pounds.

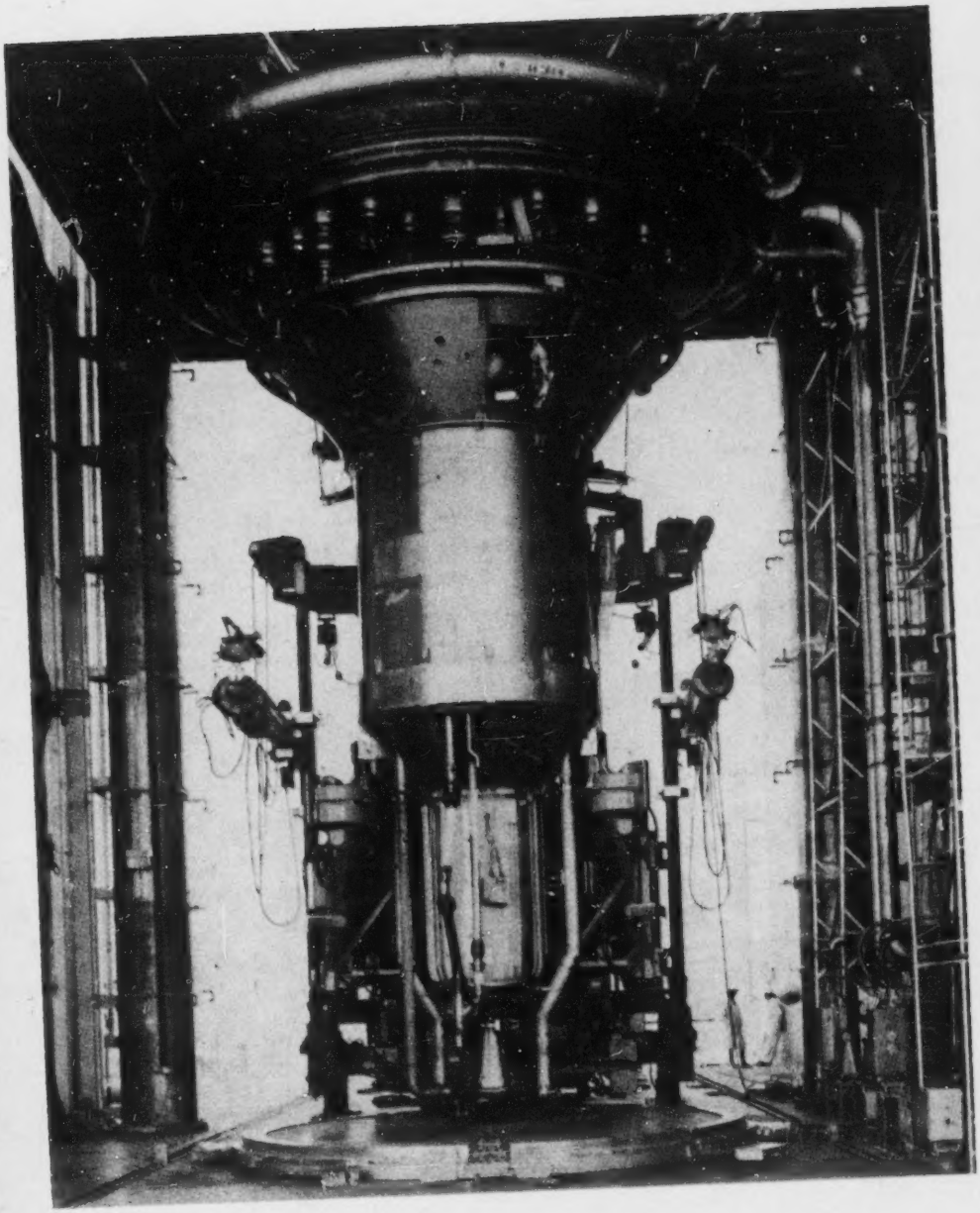

FIGURE 3 - NERVA/XE ENGINE AT TEST STAND

The technology development phase of the NERVA program was successfully completed with the NRX-A6 reactor test and the XE-Prime engine test. The feasibility questions had all been answered satisfactorily, the necessary development information had been obtained and reactor endurance capability of greater than 60 minutes at full temperature and power had been demonstrated. Development of a flight engine was ready to proceed in 1971 when the NERVA program was terminated.

B. Nuclear Extended Range aircraft (NuERA)

This study for the U.S. Air Force[9] was initiated in 1966 and had the basic objective of assessing the feasibility of manned nuclear aircraft propulsion using state-of-the-art reactor technology. The reference design parameters which guided the study included a reactor plant power level of 275 MW, a reactor outlet temperature of 1800°F, a design lifetime of all reactor components (including core) of 10,000 hours and a turbine inlet air temperature of 1600°F.

Concurrent with the design of the reactor system was the evaluation of system safety during normal and abnormal aircraft operations, including the potential consequences of a crash. In pursuing the liquid-metal-cooled high-temperature reactor technology specified for this study, various design options were considered. A single-phase heat transport system was chosen owing to several disadvantages of a two-phase system, particularly the larger flow-area requirements which would increase component sizes and weights. Although direct transport of the reactor coolant to the engine-turbines promised higher thermal efficiency, a primary/secondary heat transport system was selected to satisfy safety requirements and to avoid the maintenance problems and increased shielding requirements that would result from the plate-out of entrained radioactivity in the low-temperature components. The primary system was designed with two separate loops, each delivering heat to its own intermediate heat

exchanger, to provide redundancy in decay-heat removal in the event of a malfunction or damage to the system. Lithium was selected as the reactor coolant because its high specific heat and low vapor pressure would permit much smaller pipe sizes and wall thickness and lower pumping power. Existing irradiation test data related to fuel dimensional stability, fuel/clad/coolant compatibility data and thermophysical properties led to the choice of uranium-nitride as the prime nuclear fuel material. (Recent irradiation data developed under the LMFBR program indicate that fuel swelling of uranium carbide, one of the candidate NuERA fuel materials, would not be as severe as anticipated in the NuERA study).

The reactor concept resulting from the evaluation of viable design options was a lithium-cooled compact fast reactor. All the primary piping material was a columbium alloy (Cb-1Zr) as were the intermediate heat exchangers, the pumps, and the reactor vessel. The fuel pins, which also were in contact with the lithium were clad in a tantalum base alloy (ASTAR 811-C). A secondary fluid, liquid sodium-potassium (NaK), was used to transfer the reactor thermal energy to the engines. It exited the shell of the intermediate heat exchanger at 1700°F and flowed to the engine heat exchanger. In this engine counter-flow exchanger, the NaK was cooled to 1300°F as its energy was transferred to the air stream, thereby replacing the normal combustor function in the engine. Isolation valves were included in each secondary loop to provide shutoff capability if required in the event of an engine failure.

As shown in Figure 4, the reactor with its primary shield was mounted vertically with the vertical centerline laterally offset aft from the center of a spherical containment vessel. The intermediate heat exchangers, primary pumps and the shield coolant system heat exchanger and pumps were installed in the crescent-shaped space provided. The banana-shaped expansion tank was located at the highest point in the compartment, and was connected to one of the

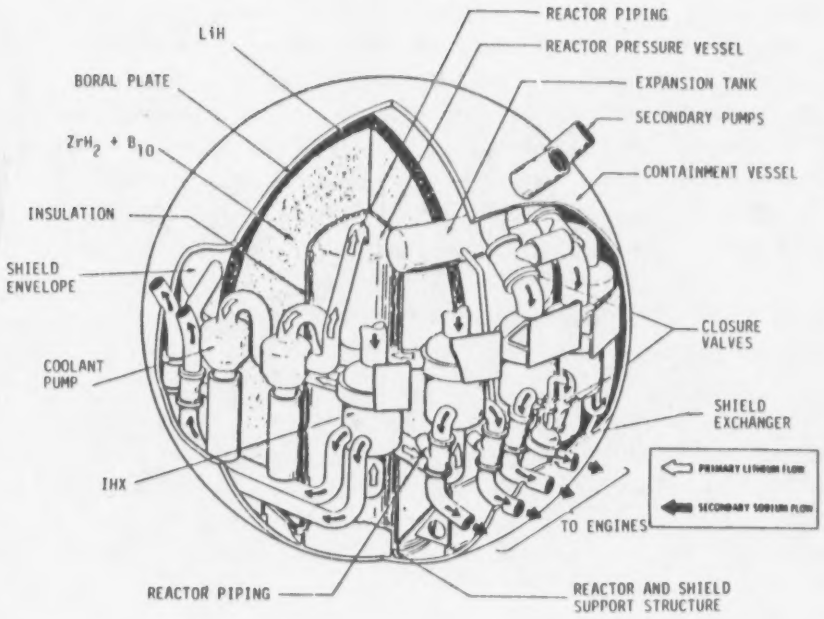

FIGURE 4 - NuERA NUCLEAR SUBSYSTEM (LIQUID-METAL)
FOR AIRCRAFT PROPULSION

reactor outlet lines. The intermediate heat exchangers, primary coolant pumps and expansion tank were supported from the containment shell. The reactor and shield assembly were mounted on a base structure attached to the lower portion of the containment shell, which was designed to withstand a 200 fps impact in any direction without rupturing.

The primary shield completely enclosed the reactor and consisted of an inner layer of tungsten inside the pressure vessel, an external layer of zirconium hydride, and an outer layer of lithium hydride. Inserted between these two major layers was a sheet of boral. The shield was compartmented and hermetically sealed to prevent the outgassing of materials and the need to contain the shield coolant.

The decay heat removal system made use of one of the primary and secondary loops. The latter was modified to contain a bypass loop which was connected to one of the secondary loops and rejected the decay heat through a liquid metal-to-air heat exchanger. The secondary coolant pump provided the pumping power.

The NuERA conceptual design developed during this extended study satisfied all reactor performance criteria and complied with specified size and weight constraints on the nuclear subsystem. Thus, the basic feasibility of using nuclear power for manned aircraft propulsion using state-of-the-art reactor technology was established.

C. Innovative Aircraft Design Study (IADS)

An extension of the NuERA study[10] was subsequently performed for the U.S. Air Force by Lockheed-Georgia Company and Westinghouse in 1976-1977 to estimate the lightest ramp weight of an aircraft configuration with a nuclear propulsion system.

Parametric analyses and design-refinement studies were conducted for conventional, canard, and spanloader aircraft configurations with payloads of 400,000 and 600,000 pounds of containerized and/or outsized cargo, a cruise Mach number of 0.75, an emergency range of 1000 nautical miles on chemical fuel, and a field length of 9000 feet. The canard configuration was selected for detailed analysis since it had the lowest ramp weights of the three configurations for both payloads.

Analyses of several Rankine and Brayton nuclear propulsion cycles resulted in the selection of an open-Brayton turbofan cycle for a reference aircraft. The selection was made on the basis of the extensive data background and low weight of the cycle. Of all the cycles considered, only a non-recuperated closed Brayton cycle with a dual-mode engine was found to be lighter in weight than the selected cycle. However, this closed Brayton cycle was excluded from consideration in the IADS study because an adequate data base was lacking.

The reference aircraft design conforming with mission requirements had a ramp weight of 1,556,000 pounds and served as a basis for assessing the sensitivity of the design to variations in the mission requirements, in advanced technology applications, and in the nuclear operation and design philosophy. A 13.1-percent reduction in ramp weight to 1,353,000 pounds was achieved by adopting an alternate nuclear operational design philosophy. Features of this alternative included special shaping of the shield, use of the emergency range chemical fuel for shielding, and full-power reactor operation for all normal flight phases with half-power for emergencies. The use of composite materials for 40 percent of the structural weight of the reference aircraft produced a 13.5-percent savings in aircraft ramp weight relative to an all-aluminum aircraft.

D. Nuclear Bi-Brayton System

Early Westinghouse studies of nuclear aircraft propulsion concepts focused on liquid-metal-metal-cooled fast reactors (NuERA) using the open-Brayton cycle and a high temperature intermediate heat exchanger which presented design problems and weight penalties. Subsequent investigations[11] of alternative nuclear propulsion systems indicated that a Bi-Brayton cycle utilizing an advanced high-temperature gas-cooled reactor was a promising concept.

The gas-cooled reactor selected for this concept made use of already proven technologies, primarily from the NERVA nuclear rocket program and from commercial gas-cooled reactors. The reactor was a helium-cooled, graphite-moderated, epi-thermal reactor with TRISO-coated fuel beads dispersed in extruded graphite elements. It had a lateral support system to maintain core bundling and a beryllium radial reflector with control drums.

The Bi-Brayton cycle eliminated the need for high temperature capabilities in the engine and intermediate heat exchangers and permitted the coupling of a state-of-the-art gas-cooled reactor. Shielding criteria and materials for the reactor were the same as for the NuERA system. The arrangement of reactor components within the containment vessel is shown in Figure 5. Figure 6 contains a system schematic and reveals how the physical separation of the primary and secondary energy transport loops was achieved; system temperatures are also shown, including those for the heat exchangers which are substantially lower than those in a comparable NuERA system. Another advantage of these low temperatures was that concentric stainless-steel supply and return lines could be used for the helium secondary system, thereby reducing the piping weight and eliminating the need for insulation.

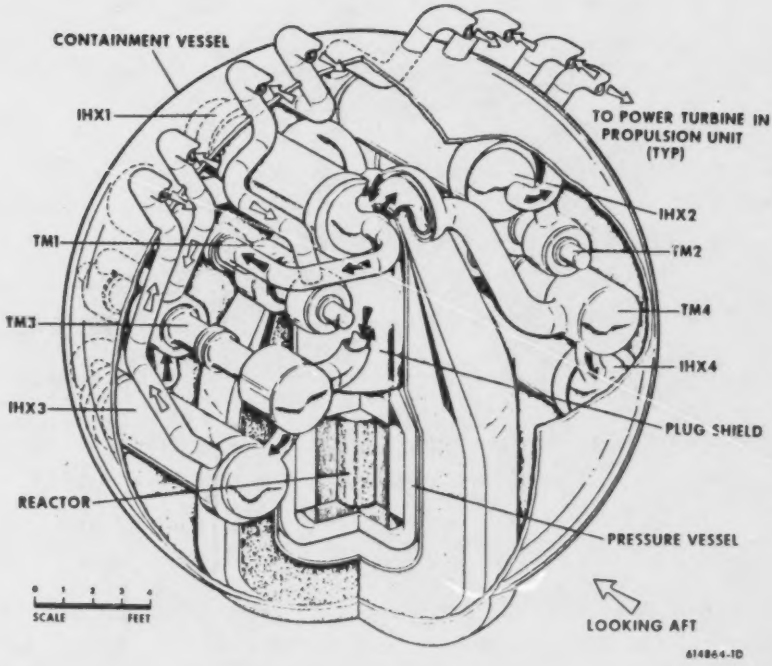

FIGURE 5 - BI-BRAYTON (GAS-COOLED) NUCLEAR SUBSYSTEM FOR AIRCRAFT PROPULSION

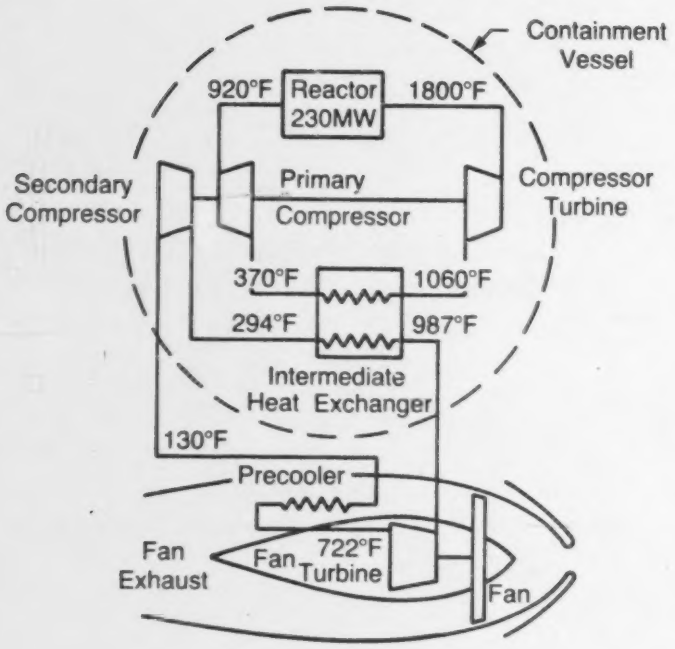

FIGURE 6 - SCHEMATIC DIAGRAM OF BI-BRAYTON AIRCRAFT PROPULSION SYSTEM

Table 2 reveals the powerplant weight reductions obtainable with a Bi-Brayton system in comparison with those of the liquid-metal concept using the closed Brayton cycle.

E. Summary

In summary, the NERVA program demonstrated the feasibility of high-power-density, gas-cooled reactors for space applications and left a broad technology legacy for future power and propulsion programs. The Nuclear Extended Range Aircraft (NuERA) and Innovative Aircraft Design Study (IADS) work verified the technical and operational viability of using a high-temperature, liquid-metal-cooled reactor for manned propulsion. The follow-on Nuclear Bi-Brayton System study revealed that a propulsion system using a gas-cooled reactor would have attractive design and weight advantages. Numerous proprietary studies on lightweight gas-cooled and liquid-metal reactor power and propulsion systems have been performed by Westinghouse since the programs described above were completed and have generally validated these results.

On the basis of this extensive participation in the design, development and testing of lightweight, high-temperature reactor power systems, Westinghouse believes that 1) the feasibility of using gas-cooled or liquid-metal-cooled reactors for aerospace power and propulsion applications has been firmly established and 2) the existing technology base justifies high confidence that an aerospace reactor development program could meet DOD requirements on performance, cost and schedule if the program is initiated promptly with a firm and clearly defined mission.

TABLE 2

COMPARISON OF SYSTEM WEIGHTS FOR
LIQUID-METAL (NuERA) AND GAS-COOLED (BI-BRAYTON)
NUCLEAR AIRCRAFT PROPULSION SYSTEMS

Propulsion Concept	Liquid-Metal NuERA	Gas-Cooled Bi-Brayton
System Elements	Subsystem Weights (1000 lb)	
Nuclear Subsystem	391.3	419.3
NSS Auxiliaries	15.0	15.0
Piping & Engine HX	122.7	32.3
Turbine & Gearing	---	6.4
Engines	81.0	70.3
JP Fuel System	3.1	3.1
JP Fuel	134.6	122.1
Total System Wt.	747.7	668.5

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IV. NUCLEAR SPACE POWER SYSTEM CANDIDATES

The reactor/power conversion system options listed in Table 3 represent the major candidates that are being evaluated in the ongoing SP-100 program whose ultimate objectives are to design, test and deploy an advanced space power system. While all combinations of the nuclear heat sources and power conversion systems are deemed to be technically feasible, trade-off studies and evaluations will determine the power plant system(s) most attractive for the particular mission(s) required by the ultimate users. The attractiveness will, of course, be measured in terms of weight and volume of the power plant system, reliability, survivability, safety, technology development requirements (including schedule and cost), and the cost of the initial and serial production units.

A brief technical description of two space reactor concepts developed by Westinghouse is provided below for the purpose of demonstrating how the existing technology base can be applied to a space power system application in the hundred-kilowatt class. The gas-cooled compact reactor is based on NERVA and commercial HTGR technology whereas the liquid-metal-cooled compact reactor concept draws from the LMFBR development program and prior aerospace nuclear propulsion and power programs.

A. Gas-Cooled Compact Reactor

The Gas-Cooled Compact Reactor (GCCR) is a leading nuclear heat source concept for an advanced space power system. A cutaway view of the GCCR is shown in Figure 7. The fuel is in the form of coated enriched uranium carbide (UC_2) beads contained in extruded graphite fuel elements. The reactor coolant is helium for megawatt-class power levels. Xenon may be added to the helium for hundred-kilowatt class power levels to increase the coolant molecular weight, thus allowing the use of compact radial flow Brayton cycle machinery. At the higher power levels, axial flow Brayton cycle components will be required for which a single constituent helium gas is acceptable. Coolant enters and leaves the reactor vessel through concentric pipes

TABLE 3

SPACE POWERPLANT REACTOR/POWER CONVERSION OPTIONS (REFERENCE 7)

NUCLEAR HEAT SOURCE

Gas-Cooled Reactor
Liquid-Metal-Cooled Reactor
Heat-Pipe-Cooled Reactor

POWER CONVERSION SYSTEM

Thermoelectric
Thermionic
Brayton Cycle
Rankine Cycle
Stirling Cycle

HEAT REJECTION SYSTEM

Heat Pipe
Pumped Fluid/Fins
Pumped Fluid/Heat Pipe Radiators

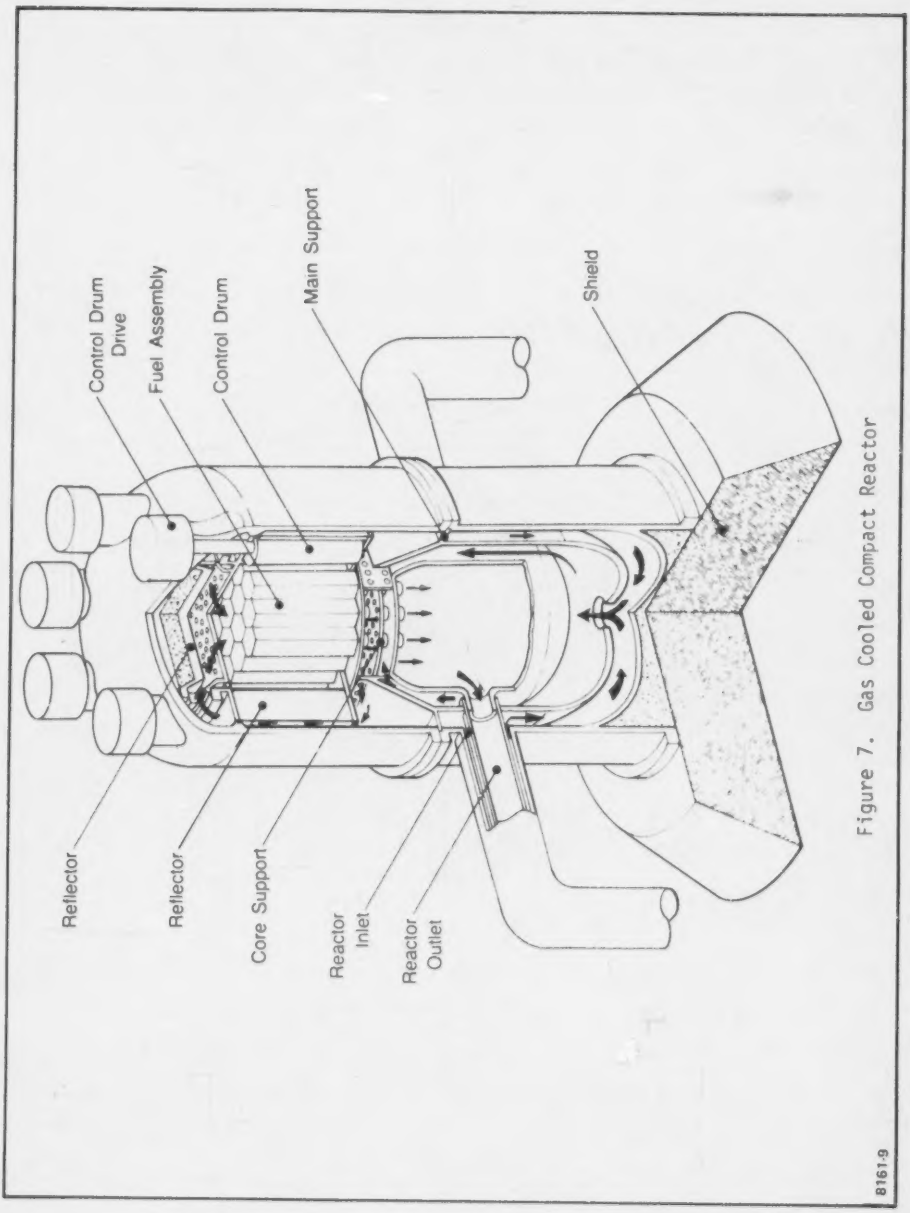

Figure 7. Gas Cooled Compact Reactor

Westinghouse Proprietary

as shown in the figure. The reactor is supported within the pressure vessel at the hot end and is equipped with both radial and axial reflectors. Control is effected by control drums in the reflector rotated by actuators mounted on one end of the vessel. The GCCR is based on well developed technologies derived from the NERVA and HTGR power reactor programs. The reference power conversion system is the direct Brayton cycle.

The principal features of the GCCR are summarized in Table 4. The initial version of the GCCR would have a fuel bead comprised of a UC_2 kernel surrounded by a graphite buffer shell and a pyrolitic carbon outer shell. The fuel bead is established technology in the NERVA program and offers a relatively high fuel loading density. The burnup and power density for compact reactor applications are lower than in NERVA. The reactor outlet temperature for the initial version is 1370 K. This temperature is consistent with the use of superalloy structural material in an arrangement where the structure is cooled by gas at reactor inlet temperature.

The improved version of the GCCR is predicated on an advanced fuel bead design with higher fuel loading densities and the use of a refractory metal alloy structural material. This version is expected to achieve a reactor outlet temperature of 1650 K and operate at somewhat higher reactor power density.

B. Liquid Metal-Cooled Compact Reactor

The Liquid Metal-Cooled Compact Reactor (LMCR) is another attractive candidate for a hundred-kilowatt class space power system. A cutaway view of the conceptual LMCR designed by Westinghouse is shown in Figure 8. The fuel is in the form of enriched uranium carbide (UC) pellets which are clad in a fuel rod configuration. The reactor coolant is liquid lithium, rather than liquid sodium used in the LMFBR, to permit high reactor outlet temperatures. Coolant enters

TABLE 4

GCCR - GAS COOLED COMPACT REACTOR

Generic features

- Graphite moderated, noble gas-cooled reactor
- UC_2 fuel beads in extruded graphite fuel elements
- Based on well developed technologies (NERVA & HTGR)
- Minimum development effort

Initial version

- Duplex fuel beads can be considered because of the lower burnup
  (0.5% to 16% in 7 years of full power life) and low power densities
- 1370 K reactor outlet temperature
- Superalloy structural material

Improved version

- Advanced fuel bead design
- 1650 K reactor outlet temperature
- Refractory metal alloy structural material

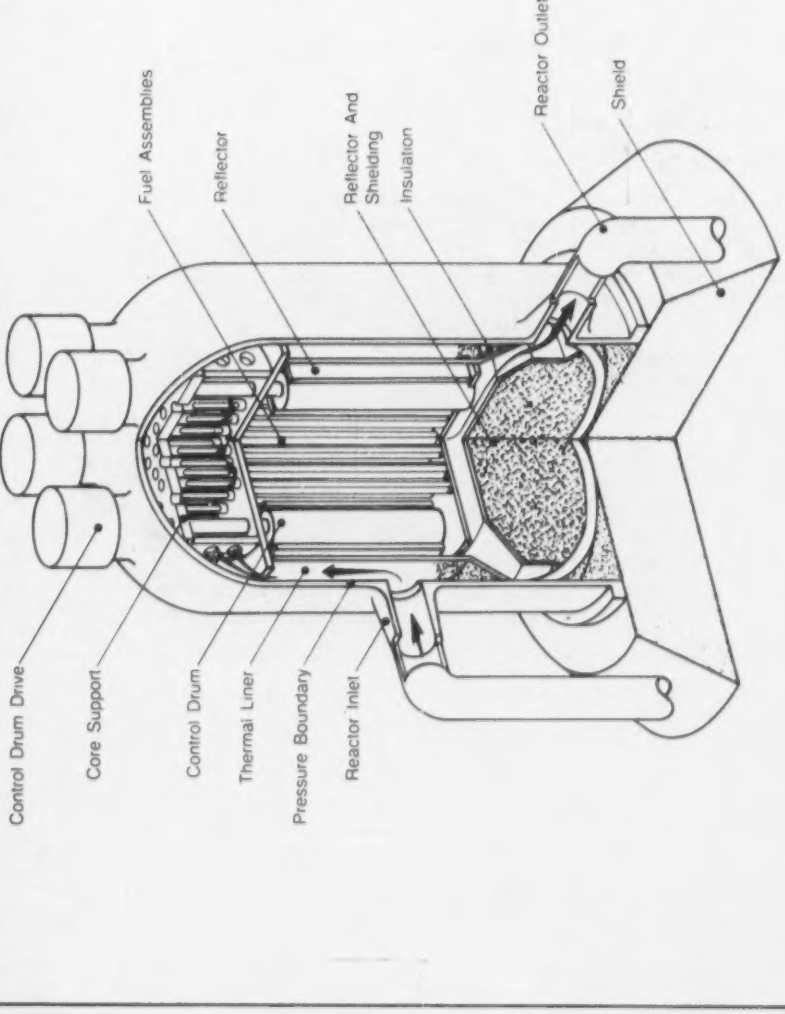

Figure 8. Liquid Metal Cooled Compact Reactor

Westinghouse Proprietary

TABLE 5

LMCR - LIQUID METAL COOLED COMPACT REACTOR

Generic features:

- Lithium-7 coolant (superior heat transfer capabilities)
- Fast reactor (compact reactor and low specific weights)
- Significant developments of similar systems (LMFBR, SNAP-50, ANP, FMIT)

Initial version:

- UC fuel pellets in fuel rods (non-vented because of low burnup and low fission gas release)
- Nb-base cladding material (high creep strength)
- Helium bond (low power density)
- 7 year full power life
- 1370 K reactor outlet temperature
- Nb-base structural material (high strength and compatibility with lithium)

Improved version:

- UC fuel in advanced refractory Metal alloy clad (higher creep strength than Nb-base)
- Helium bond
- 1650 K reactor outlet temperature to maximize power conversion efficiency
- Advanced refractory metal alloy structural material

the reactor vessel as shown in the figure, passes outboard of the reflector to the core inlet, then through the fuel assemblies to the reactor outlet. The reactor is equipped with a radial reflector containing control drums which are rotated by actuators mounted on one end of the vessel. As in the GCCR, it is probable that control elements internal to the core will also be required for the initial version at the higher power levels. The LMCR is based on significant developments of similar systems in the LMFBR, FMIT, SNAP-50 and ANP programs. The reference power conversion system is the indirect potassium - Rankine cycle.

The principal features of the LMCR are summarized in Table 5. The initial version of the LMCR would have UC fuel pellets in non-vented fuel rods clad with refractory alloy for high creep strength. Helium bonding can be adopted because of relatively low burnup and power densities. The UC fuel rods, coupled with refractory alloy structural material, permit a reactor outlet temperature of 1370 K. The improved version of the LMCR is predicated on development of advanced refractory alloys with higher creep strength for the fuel rod clad and structural materials. This version is expected to achieve a higher reactor outlet temperature and operate at somewhat higher reactor power density. Another goal for the improved version is the elimination of the need for control elements internal to the fuel assemblies by incorporation of burnable poison material in the core.

V. SYSTEM DEVELOPMENT AND DEMONSTRATION

The overall logic for development of a space power reactor is shown in Figure 9. The first stage of this program involves further evaluation of the primary reactor concept candidates concluding in selection of the reactor concept. It is important during this stage that a set of expected power plant requirements be defined with which to assess alternate design approaches and formulate meaningful comparisons. With a reactor concept identified and powerplant requirements defined, the program proceeds in parallel with preliminary design and technology development. The purpose of technology development activities is to validate the application of the existing data base for compact reactor conditions. This data base is extensive in the case of a gas-cooled reactor concept, as illustrated by the series of successful tests in the NERVA nuclear rocket program. The NRX series of reactor tests culminated in the NRX-A6 where a full power test at 1100 MW was successfully completed at a reactor outlet temperature of 2270K. Nuclear rocket reactor tests led to a simulation of an engine system configuration in the NRX/EST test article shown in Figure 10. These elements of the nuclear rocket program form a basis on which to formulate development activities for the gas-cooled reactor concept. Preliminary design, including interaction with safety and reliability analyses, leads to early initiation of component development activities to form the basis for final design of the demonstration reactor. Completion of demonstration reactor final design, supported by component qualification and fuel tests, leads to fabrication and assembly of the demonstration reactor test. Several candidate facilities for demonstration reactor testing have been identified including the nuclear rocket facilities at the Nevada Test Site, the UHTREX facility at LANL, NASA's Plum Brook reactor test facility and ANP test facilities at Idaho. The requisite safety activities and approvals complete preparations needed for the demonstration reactor test.

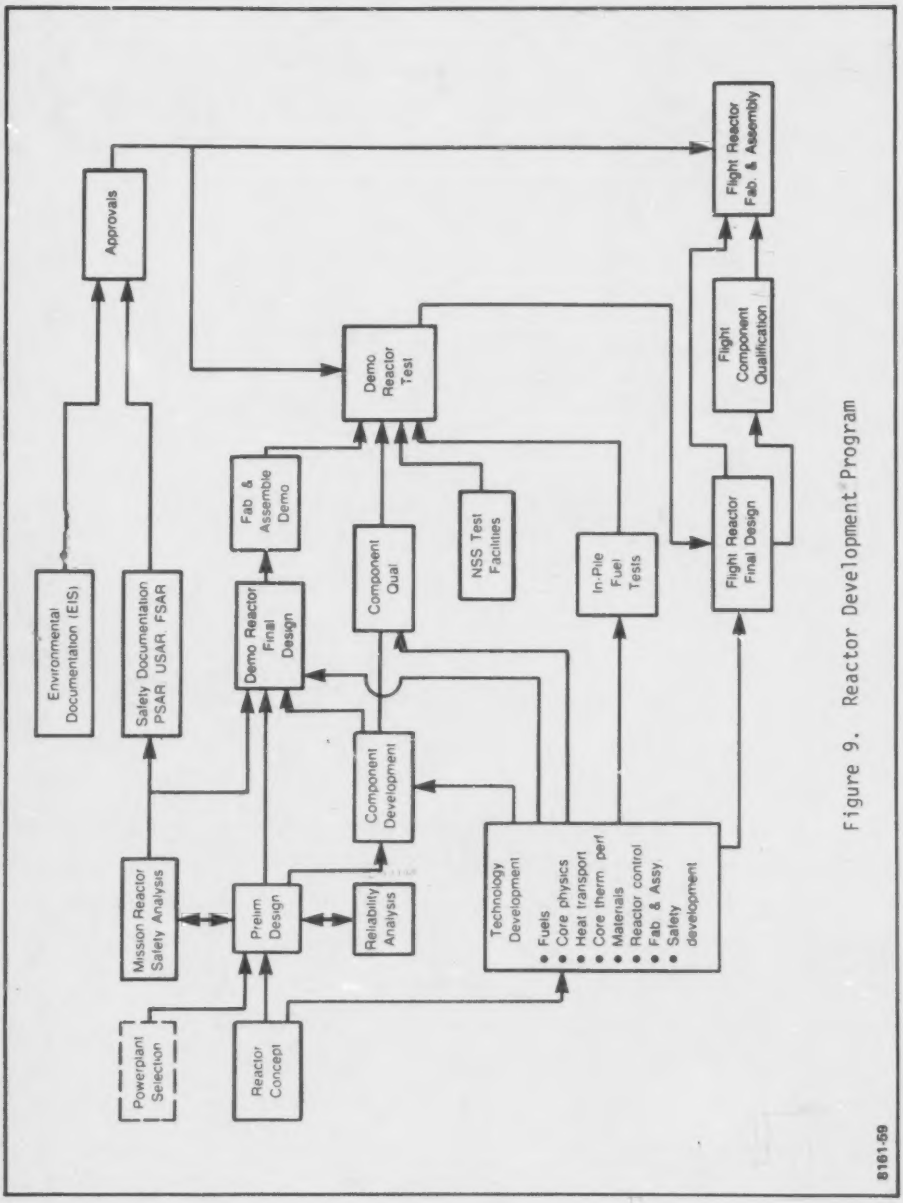

Figure 9. Reactor Development Program

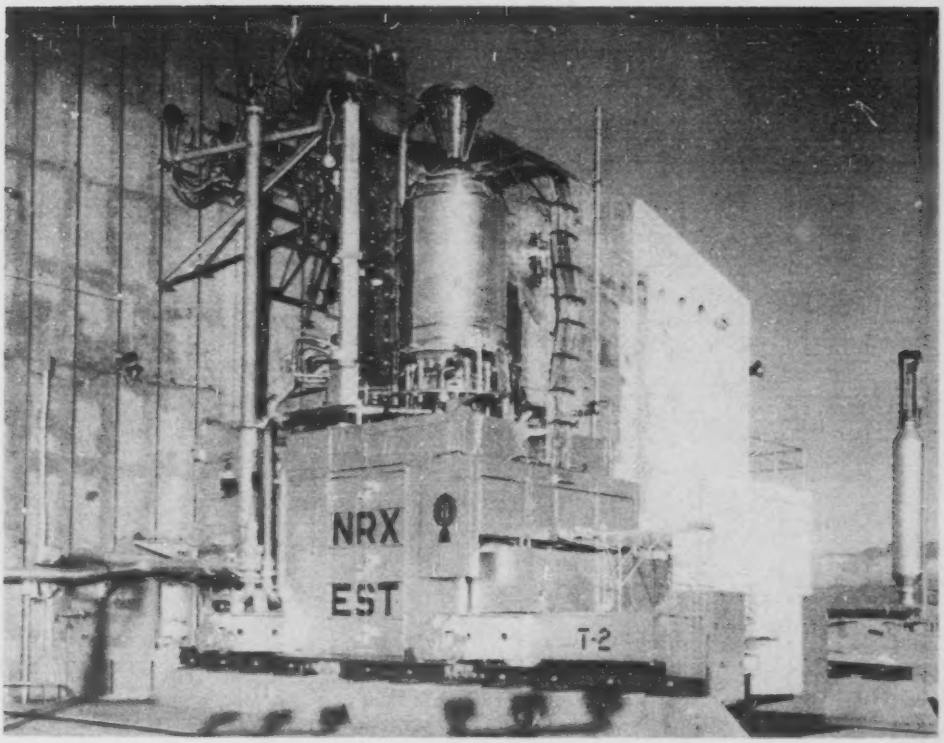

Figure 10. Westinghouse Designed NERVA Nuclear Rocket NRX Engine System Test (EST) Installed at Test Cell A, Nevada Test Site.

Flight reactor final design is initiated in parallel with preparations for the demonstration reactor test. This activity is based on inputs from technology and component development and from demonstration reactor progress and leads to qualification of flight components followed by fabrication and assembly of a flight reactor. Flight safety analyses, reports and approvals are required to complete the flight reactor system. Reactor program information, coupled with a characterization of the location and features of key development and launch facilities, will be utilized in the preparation of appropriate Environmental Impact Statements to obtain requisite NEPA approvals.

VI. SAFETY CONSIDERATIONS

The design, development and deployment of a space nuclear system must be approached with a recognition of the safety implications of using a nuclear reactor as a heat source for the production of electrical power in space. The unique features of this application, as compared to a ground based reactor, are the physical environments that may be imposed on the reactor while transferring it to the desired orbit in space, the lack of provision for the ultimate containment of radioactivity if it is released from the reactor system and the large area of the earth over which it may have a radiological impact in the event of an accident or for its ultimate return to earth.

Top level DOE requirements contained in "Nuclear Safety Criteria and Specifications for Space Nuclear Reactors" (OSNP-1) must be met by including inherent safety features and safeguards in the basic reactor design. The more important requirements are listed in Table 6. In addition, the general philosophy and, where applicable, specific design requirements of 10CFR50, Appendix A, "General Design Criteria for Nuclear Power Plants" must be included in the design specifications for systems, subsystems and components.

The safety plan for a space nuclear system must address the principal elements of the flight system mission with somewhat different concerns for each. These elements are as follows:

- Ground Handling and Transportation - The primary safety concern prior to installation at the launch pad is to maintain the reactor in a subcritical state.

- Prelaunch and Launch - here again, the principal safety concern is to maintain the reactor subcritical in the event of incidents such as propellant fire, shrapnel from an explosion or high velocity impact during launch.

TABLE 6

NUCLEAR SAFETY DESIGN REQUIREMENTS FOR SPACE APPLICATION

- The reactor shall be designed to remain subcritical if immersed in water or other fluids (such as rocket propellants) to which it may be exposed.
- The reactor shall have a significantly effective negative power coefficient of reactivity in the power range.
- The reactor shall be designed so that no credible launch pad accident, range safety destruct actions, ascent abort or reentry from space resulting in Earth impact could result in a critical or supercritical geometry.
- The reactor shall not be operated (except for zero power testing yielding negligible radioactivity at the time of launch) until a stable orbit or flight path is achieved and must have a reboost capability from low-earth orbit if it is operated in that orbit.
- Two independent systems shall be provided to reduce reactivity to a subcritical state. They shall not be subject to common cause failure.
- The reactor shall be designed to ensure that there is an independent shutdown heat removal system or independent heat removal paths within the heat transport system to provide decay heat removal.
- The unirradiated fuel shall pose no significant environmental hazard.

- o Ascent - the additional concern during this phase is that of re-entry in the event of a suborbital abort.

- o Orbital - for this phase, DOE requirements call for long term decay of fission products following reactor operation by placing the reactor in a long life orbit at the conclusion of the mission. Thus, it will be necessary to insure that the reactor and the load path to boost thrusters remain intact to permit delivery to a long lived orbit at the conclusion of the mission. In addition, design features of the reactor are to accommodate thermal disassembly by aerodynamic heating upon reentry to disperse the material over a large area, thereby precluding any concern for subsequent criticality.

In addition to the flight system elements noted above, ground testing safety programs will need to be formulated for reactor tests during the development and qualification phases of the program. Finally, it is anticipated that a Program Environmental Impact Statement (EIS) will be required from the lead federal agency to support Congressional authorization and appropriation of the funds required to develop the Nuclear Power System.

VII. CRITICAL ISSUES

In a program as sophisticated as the development of an advanced space nuclear power system, many diverse factors will determine if and how such a program can meet its objectives. Although technical considerations will have a major influence on program success, the extensive base of technology and experience that has been acquired through the SNAP and NERVA space reactor programs and the liquid-metal fast breeder program indicates that technology need not be a critical issue. As long as program direction does not involve a substantial departure from this base, then time-consuming and costly R&D can be minimized and system development and demonstration can proceed at an acceptable technical risk within the required deployment schedule.

However, there are two issues of a programmatic nature which are considered by Westinghouse to be critical to the future success of this emerging national program. The first issue concerns the necessity of firmly establishing a mission and associated functional requirements early in the program so that system development need not be interrupted by major design changes to accommodate revisions in performance specifications. Such a vacillation in program direction will lead to loss of public support in spite of a highly successful technical approach.

The second issue deals with the obvious importance of adequate and stable funding which a development program must receive in order to maintain a cost-effective pace and motivated design team. Although Westinghouse has been able to carry the Clinch River breeder reactor design to approximately 90% of completion during an extended period of controversy, delay and funding constraints, the Project has been severely wounded by the resulting escalation in estimated plant cost.

An increased sensitivity of the Congress and responsible federal agencies as well as the nation's technical community to these critical issues will enhance the prospect that this important space development program will successfully meet all of its objectives.

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9. J. C. Muehlbauer and R. E. Thompson, "Nuclear Aircraft Innovations and Applications," in AIAA Very Large Vehicle Conference, A Collection of Technical Papers, paper 79-0846, American Institute of Aeronautics and Astronautics, Inc., New York, 1979.

10. J. C. Muehlbauer, "Innovative Aircraft Design Study, Task II, Nuclear Aircraft Concepts," LG77ER0008, Lockheed-Georgia Company, April 1977.

11. B. L. Pierce, "Nuclear Bi-Brayton System for Aircraft Propulsion," ASME Paper 79-GT-119.

Mrs. LLOYD. Thank you very much.
Mr. Rosenberg, it's your turn.

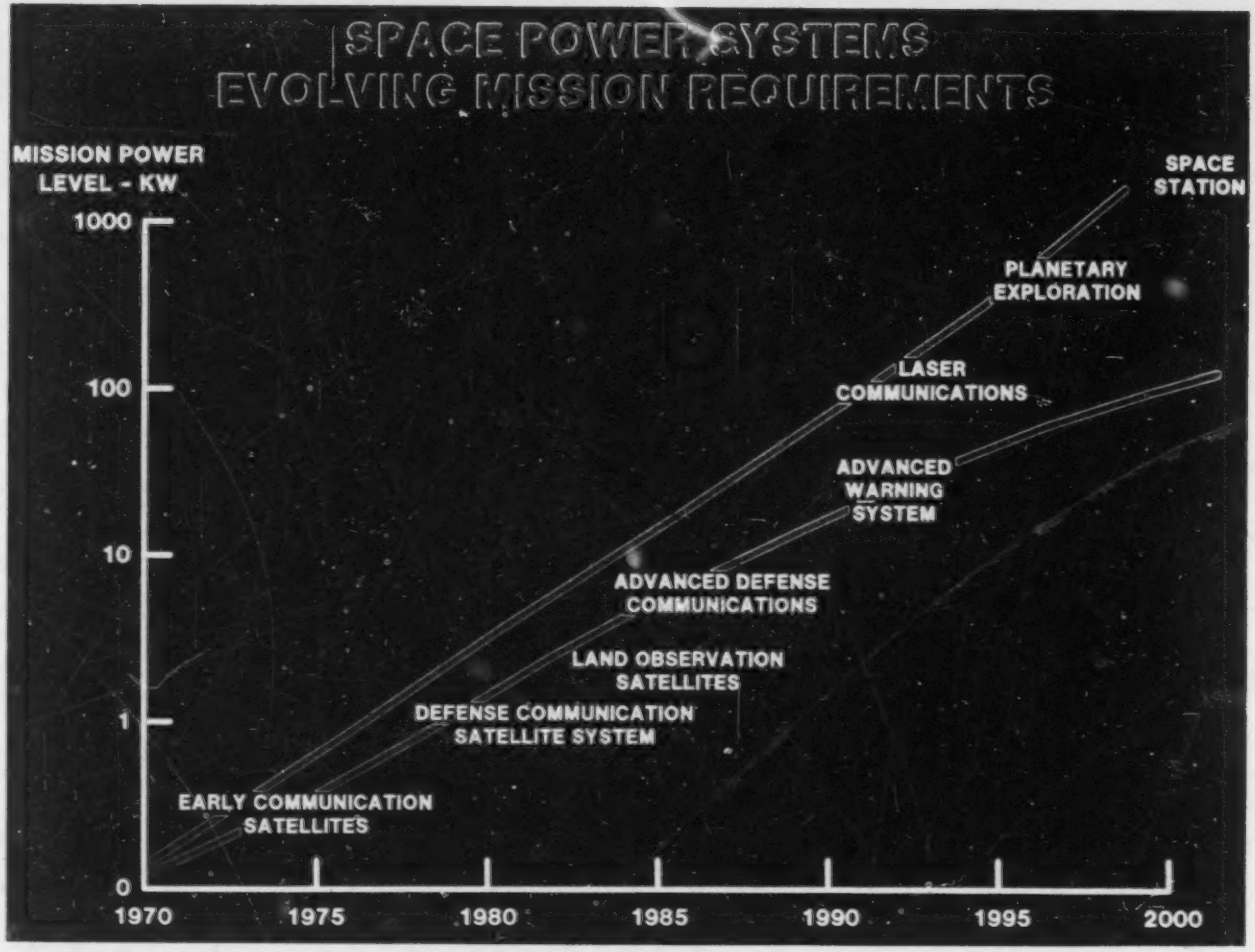
STATEMENT OF ALLAN J. ROSENBERG, VICE PRESIDENT AND GENERAL MANAGER, SPACE SYSTEMS DIVISION, GENERAL ELECTRIC CORP., ACCOMPAMIED BY DR. BERTRAM WOLFE, VICE PRESIDENT, GENERAL ELECTRIC CO., AND GENERAL MANAGER, NUCLEAR FUEL AND SPECIAL PROJECTS DIVISION.

Mr. ROSENBERG. Thank you, Madam Chairman, and members of the subcommittee.

It is a privilege for both Dr. Wolfe and me, representing General Electric, to present our views on space nuclear power. As a producer of spacecraft and power sources for national missions for over 20 years, I feel strongly that space nuclear power capability be fully developed for future mission applications.

NASA, DOD, DOE, and their industry partners have succeeded in achieving many complex missions using available space power technology. However, recent studies indicate that future missions will require significantly larger power than employed to date, which can most effectively be filled by a nuclear alternative.

To date, spacecraft power has been provided primarily by solar cells and batteries, chemical fuel cells, and nuclear isotope devices, progressing from early space missions using tens of watts to today's missions requiring kilowatts.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DEFENSE COMMUNICATION
SATELLITE SYSTEM
EARLY COMMUNICATION
SATELLITES

CHART 1

Chart 1 is an attempt to show the evolving mission requirements in terms of power and time of mission application.

Early communications satellites—such as Westar—required 200 to 300 watts. The Defense Communications Satellite DSCS II used 500 watts, and DSCS III, the most recent military communications satellite, which was designed and built by General Electric, utilizes 1.2 kilowatts. Advanced Defense Communications Satellites—Milstar, for example—will be three to four times that power level.

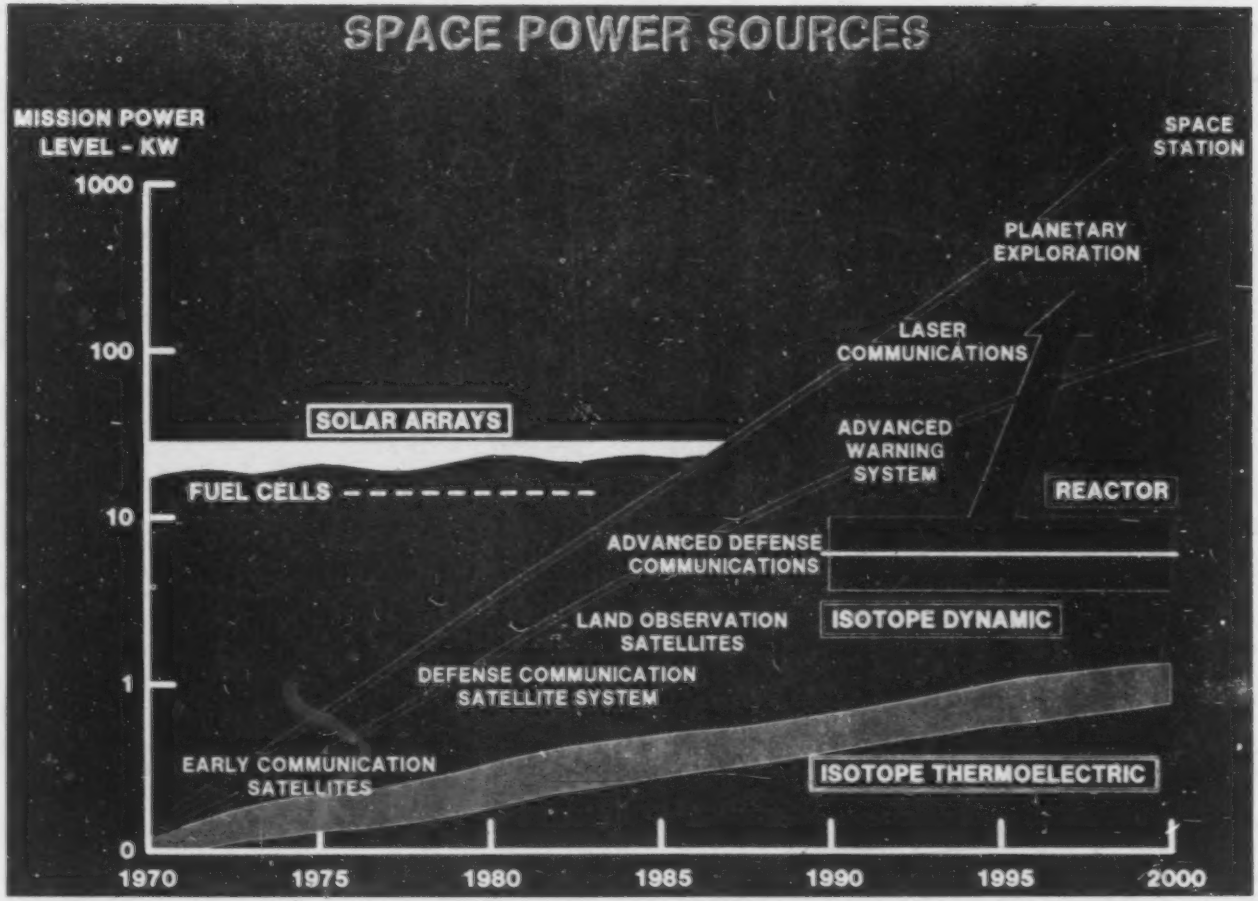
Land observation satellites have had a similar growth in requirements from 500 watts on GE's Landsat 1 to 2 kilowatts on Landsat 4.

The advanced warning systems planned today will employ even more sophisticated sensors as their payload, with systems of the 1990's demanding above 10 kilowatts.

A laser communication satellite, linking defense command centers with submerged submarines, would require in the range of 25 kilowatts or more for the laser beam to penetrate the ocean surface.

Now, this country has also enjoyed outstanding success with planetary exploration programs. Sending larger experimental payloads to distant planets in reasonable time periods, thereby increasing the value of scientific missions, would extend power requirements to the halfmegawatt range.

Perhaps the largest amount of power will be required by a space station. Expansion of today's work, leading to a factory in space, will initially require power sources above the 100-kilowatt level and could rise to the megawatt level in the next century.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ADVANCED WARNING SYSTEM
REACTOR
SOLAR ARRAYS
FUEL CELLS
ADVANCED DEFENSE COMMUNICATIONS
ISOTOPE DYNAMIC
LAND OBSERVATION SATELLITES
DEFENSE COMMUNICATION SATELLITE SYSTEM
EARLY COMMUNICATION SATELLITES
ISOTOPE THERMOELECTRIC

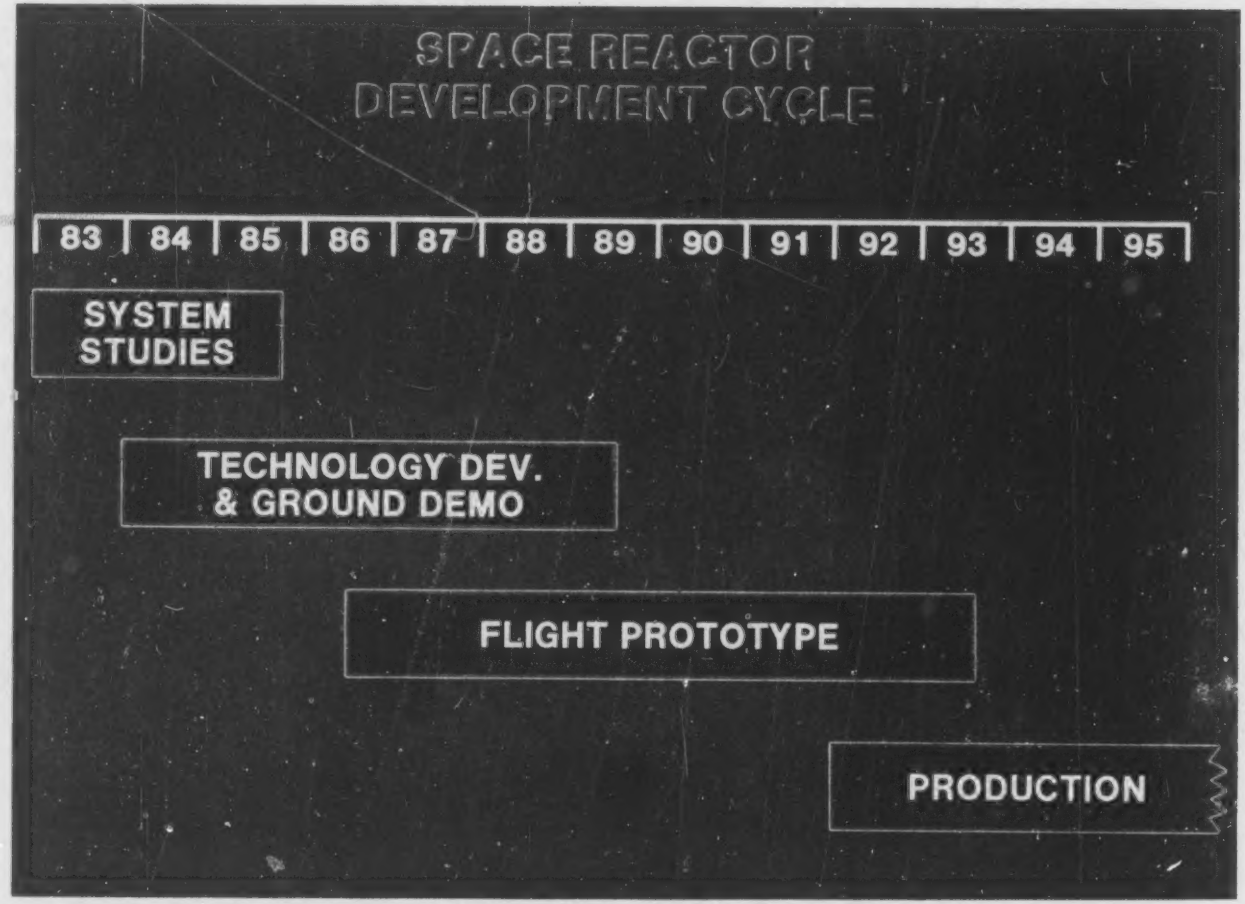
CHART 2

Chart 2 superimposes on the first, the sources which would be available to provide needed power requirements.

The upper limits of currently available space power sources have been studied. The approximate practical limit of nuclear isotopes, which occurs when used to operate a turbine in a dynamic mode, is reached at about 10 kilowatts; fuel cells can be employed in the range of approximately 15 to 20 kilowatts; and solar arrays reach their practical limit at 25 to 30 kilowatts. Missions of the future will require power levels that far exceed these limits.

At General Electric, we have looked at many ways to provide the higher power requirements of the nineties and beyond. Nuclear sources appear most attractive on the basis of size, weight per watt of power, as well as potential cost. Advanced solar arrays systems are expected to generate 10 to 20 watts per pound at most. The present SP-100 kilowatt reactor study has a goal of 15 watts per pound, with increased maneuverability and survivability. Studies indicate that reactor systems in that range could provide approximately 25 to 50 watts per pound as development proceeds. Space nuclear reactors in the megawatt range will provide even better power density.

The need is emerging and the technology is available. No new breakthrough is required although detailed development and application engineering, however, must be completed to insure the effective transition to space.


SPACE REACTOR
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& GROUND DEMO
FLIGHT PROTOTYPE
PRODUCTION

CHART 3

Chart 3 shows the major schedule phases of advanced space nuclear power development. Systems studies should be concluded before 1985. Technology development should be followed with ground demonstration as soon as possible. As this critical phase progresses, the start of construction of a flight prototype would be achievable. In my estimation, it will take approximately a decade to complete the development of a safe space nuclear reactor, and the SP-100 program provides the needed start today.

Obviously, there is public concern of the safety of a space nuclear reactor. A few years ago the United Nations formally addressed the issue and the U.S. position, presented in 1980 to the U.N. required launching an appropriately shielded reactor in a subcritical mode, having designs which would prevent criticality in the event of a launch abort or premature reentry, and limitation to startup until the system achieved an orbit of sufficient duration to provide for fission product decay.

The United States has launched 22 nuclear isotope power systems and 1 experimental reactor without any safety incidents. In the three cases where the primary missions were aborted, the isotope systems posed no danger to the environment because of sound design practices.

In the fifties, GE designed and developed a number of special purpose reactors and in the sixties began work on a space nuclear reactor under contract to the previous Atomic Energy Commission. GE has provided isotope generators for two communication satellites, LES 8 and 9, which have had, to date, 7 years of flawless power service. The Voyager deep space probes had phenomenal success and were powered by isotope systems which we supplied. Currently, we are providing nuclear power sources for the solar polar mission and for the Galileo scientific spacecraft. These isotope systems are radioactive at launch and have successfully met all safety requirements through containment techniques.

Reactors for space application will not be radioactive at launch. With successful acquisition of orbit, the reactor can then be activated with no terrestrial hazard. Higher orbits with lifetimes of 300 years or more and planetary probes offer no hazard over the entire mission life because of the natural decay of the radioactive products during the orbit lifetime.

In the case of lower Earth orbits, there are means to raise the orbit after use. In addition, specific design of the reactor to allow breakup, burnup, and dispersion to safe levels—in the event of reentry—is possible.

Radiation environments with proper shielding at the payload can be significantly less than the normal space environment and will not create a new source of radiation in space.

I see the issue of public safety as manageable. Obviously, we must never permit any major risks and must exercise continuous vigilance, require very stringent design criteria, and extensive testing programs.

Today, we have a large community of expertise in national laboratories and industry to perform this work. The majority of these professionals have two and three decades of space nuclear experience to draw upon. They represent a national resource which can and should be utilized for the development of this program. At the

same time, we must recognize that this expertise will disappear unless new, young talent is brought into this arena through challenging bright young people to participate in this technology which is embodied in programs such as the SP–100.

The joint working committee which led to formation of a tri-agency organization to initiate a space nuclear power program deserves the full and continuing support of this subcommittee and of the full Congress.

Since technologies have advanced dramatically in the last 10 to 15 years, particularly in the nuclear area as it would apply to a practical space power system, I would like to introduce Dr. Bertram Wolfe who will address the issue of nuclear technologies today, and I thank you for this opportunity to testify.

[The prepared statement of Mr. Rosenberg and Dr. Wolfe follow:]

TESTIMONY BY

ALLAN J. ROSENBERG
VICE PRESIDENT, GENERAL ELECTRIC COMPANY
GENERAL MANAGER, SPACE SYSTEMS DIVISION

and

DR. BERTRAM WOLFE
VICE PRESIDENT, GENERAL ELECTRIC COMPANY
GENERAL MANAGER, NUCLEAR FUEL AND SPECIAL PROJECTS DIVISION

before

THE U. S. HOUSE OF REPRESENTATIVES
SUBCOMMITTEES ON ENERGY RESEARCH AND PRODUCTION

and

SPACE SCIENCE AND APPLICATIONS

on

SPACE NUCLEAR POWER

TUESDAY, MAY 24, 1983

WASHINGTON, D. C.

Chairman Lloyd, Chairman Volkmer and Members of the Subcommittees:

I am Allan J. Rosenberg, Vice President of the General Electric Company and General Manager of the Space Systems Division. It is a privilege for Dr. Wolfe and me, as representatives of the General Electric Company, to have this opportunity to present our views on the very important subject of Space Nuclear Power. As a producer of spacecraft for national missions, I feel strongly that space nuclear power capability be fully developed for future applications, and as you know, the General Electric Company has for over 20 years been actively involved in developing and producing nuclear power sources for space application. Power is a very precious commodity in space which must be very carefully metered and managed to accomplish defense, application and scientific missions.

The aerospace community, including NASA, DOD, DOE, and their industry partners have succeeded in accomplishing many complex missions using available space power technology. However, recent studies indicate that future missions will require significantly larger power sources than have been employed to date, requirements which can most effectively be filled by a nuclear alternative.

Over the history of space flight, spacecraft power has been provided primarily by solar cells and batteries, chemical fuel cells and nuclear

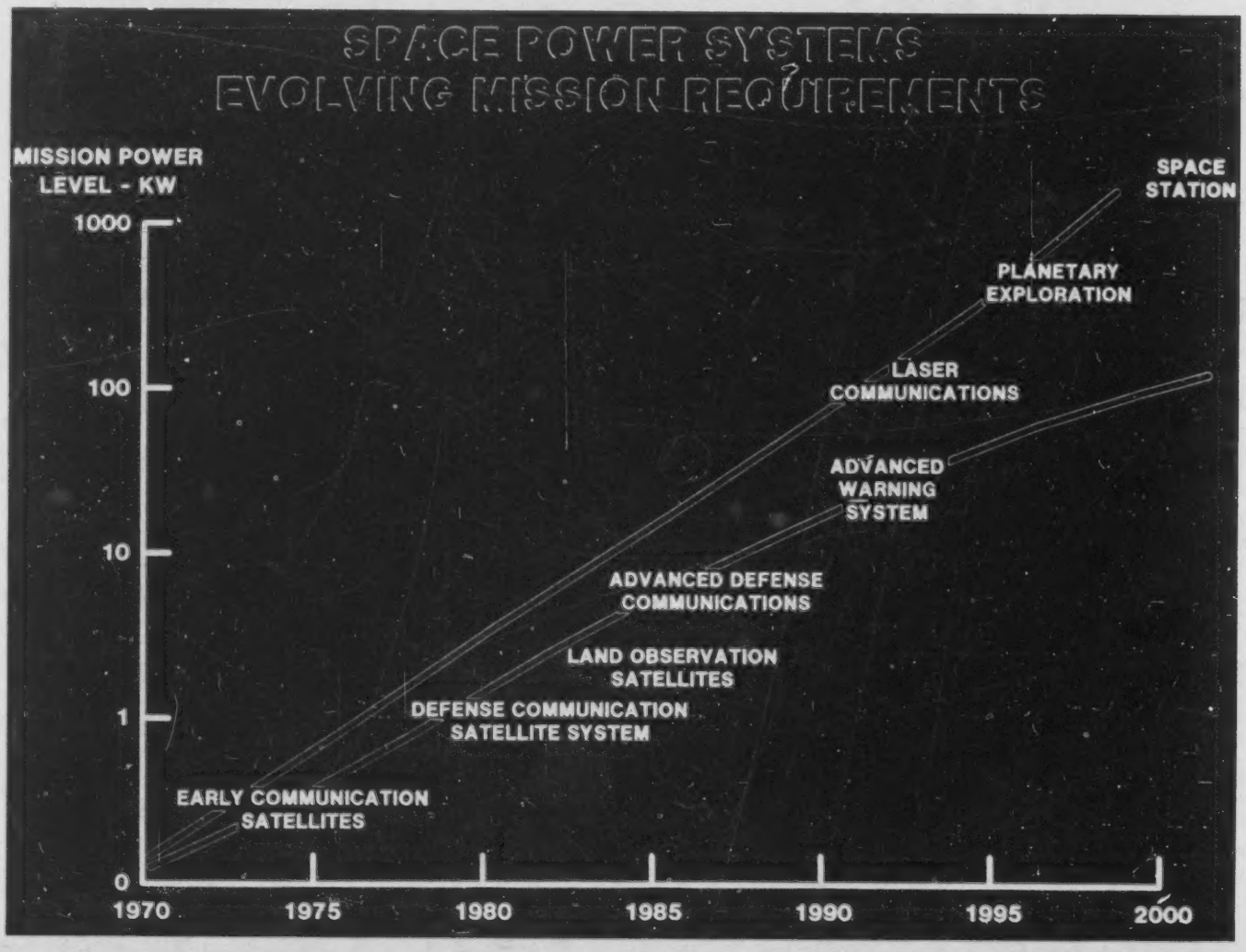
isotope devices. As mission objectives became more sophisticated and more complex, we progressed from early space missions using tens of watts to today's missions requiring kilowatts of power.

CHART NO. 1--SPACE POWER SYSTEMS EVOLVING MISSION REQUIREMENTS

Early communications satellites--such as WESTAR--required 200-300 watts of solar array power; the Defense Communications Satellite DSCS II used 500 watts; and DSCS III, the most recent military satellite, designed and built by General Electric, utilizes 1.2 kilowatts of power. The requirements for advanced defense communications satellites--MILSTAR, for example--will be 3-4 times the power required by DSCS III.

This growth in power for communications satellites results from a number of factors which include larger satellites with more communication channels; the reduction in size and cost of ground receiving stations, and crowding of the frequency spectrum which is being alleviated by using higher frequencies which in turn, require more power to penetrate adverse weather conditions.

Land observation satellites have had a similar growth in power requirements ranging from 500 watts on GE spacecraft such as Landsat 1 to two kilowatts on our Landsat 4, reflecting advances in sensor technology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derived from user requirements.

Advanced Warning Systems will employ even more sophisticated sensors as payload. As mission requirements become more demanding, spacecraft and payload technology are developed to meet new requirements and the amount of power to perform the mission also must be increased. The advanced Warning Systems of the 1990s will be in the above 10 kilowatt requirement range.

Today, there are several conceptual studies underway examining the advantages of a laser communications satellite in linking defense command centers with submerged submarines. This space mission would require 25 kilowatts or more of power for the laser beam to penetrate the ocean surface.

This country has already enjoyed outstanding success with planetary exploration programs. Studies indicate future exploration of the outer planets can be enhanced with electric propulsion engines which allow more maneuverability of the spacecraft in the vicinity of the planets and such engines would require even higher power levels. Sending larger experimental payloads to distant planets in reasonable time periods, thereby increasing the value of scientific missions, would extend power require-

ments to the half-megawatt range.

Perhaps the largest amount of power will be required by a space station incorporating materials processing. Today, government-industry teams are conducting experiments which are a precursor to space industrialization. Expansion of this work, leading to a factory in space, will initially require power sources above the 100-kilowatt level and could rise to the megawatt level in the next century.

CHART NO. 2--POWER SOURCES

In anticipation of future mission requirements, the upper limits of currently available space power sources have been studied. We believe the approximate practical limit of nuclear isotopes is reached at about 10 kilowatts when used to operate a turbine in a dynamic mode; in a static mode as a heat source for thermoelectric conversion, the limit would be approached at 1 kw; fuel cells can be employed in the range of approximately 15-20 kilowatts; and solar arrays reach their practical limit at 25-30 kilowatts. Missions of the future, as we have seen, will require power levels that far exceed these limits.

Radioisotope thermoelectric generators, which have been successfully used on interplanetary missions such as Voyager provided about 450 watts.

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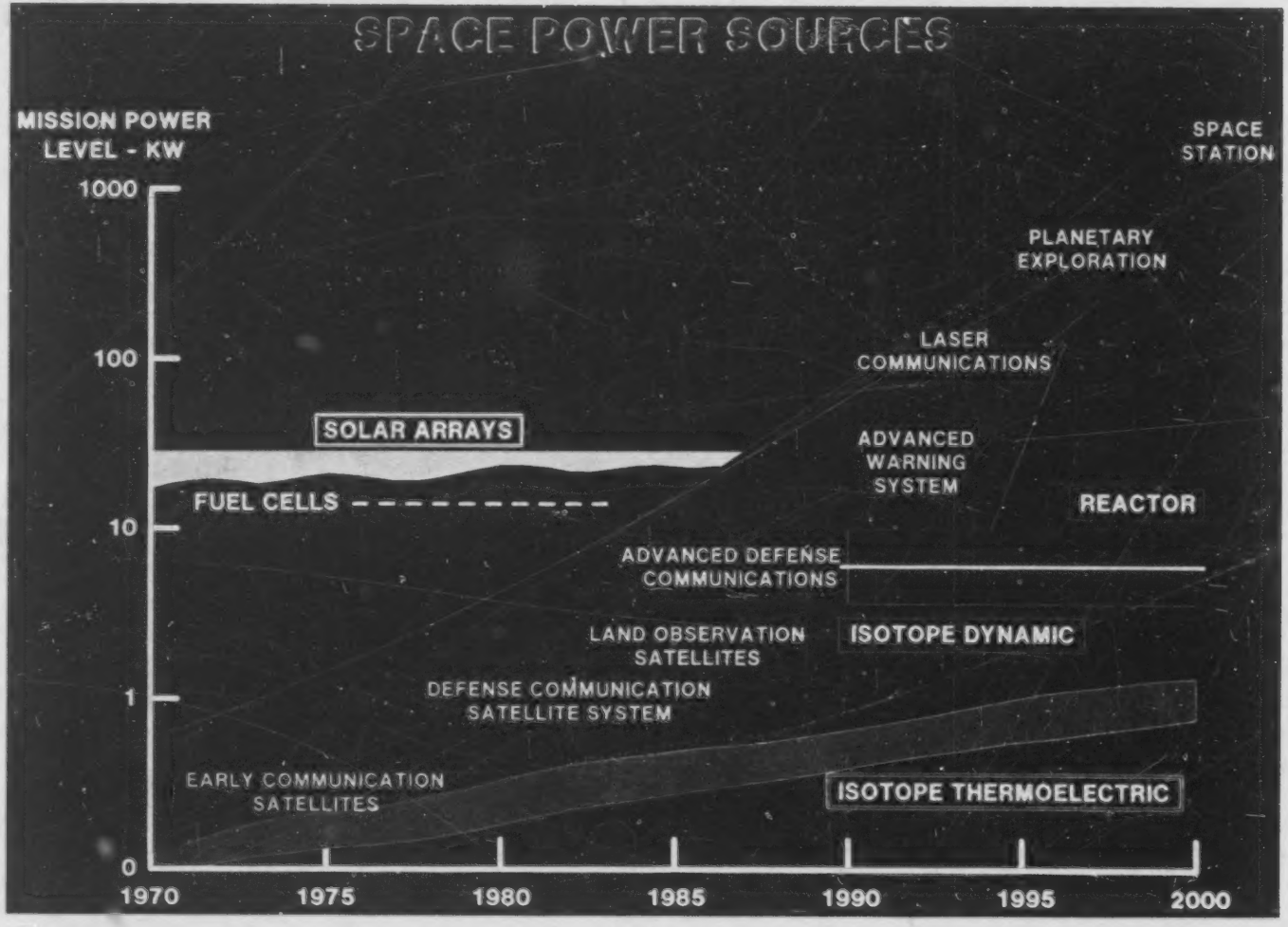
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These power sources are necessary for missions where the spacecraft cannot use a solar array because of its distance from the sun. Isotope power sources also can operate when passing through the Van Allen radiation belt as well as where long periods of darkness occur.

Chemical fuel cells were used as power sources for the Gemini, Apollo and Space Shuttle manned space flight missions. The fuel cell for Gemini, built by GE, had a one-kilowatt capacity. Apollo fuel cells generated about four kilowatts of power. The Space Shuttle fuel cells provide up to 14 kilowatts of continuous power. General Electric has performed research studies on regenerative closed-cycle systems employing fuel cells combined with a solar array. However, the limitations of solar arrays and the logistical need to resupply fuel make a high level of power impractical. Fuel cells, therefore, which can be used on missions of short duration, are not as useful for high-power multi-year missions.

The largest solar cell arrays, 2400 square feet in area, produced 16 to 17 kilowatts for the Skylab mission. Current solar cells are capable of producing about 10 watts per square foot average orbital power. Advanced cells will improve these figures. However, the weight and size

of solar arrays needed to generate high amounts of power limits their use to missions at about the 25-kilowatt level.

At GE, we have looked at many ways to provide the higher power requirements of the 1990s and beyond. In our assessment and with today's projected technology levels, nuclear sources appear most attractive on the basis of size, weight per watt of power, as well as potential cost. Advanced solar arrays are expected to generate 10-20 watts per pound at most. The present SP 100 reactor study has a goal of 15 watts per pound, with increased maneuverability and survivability. Studies indicate that reactor systems in that range will provide approximately 25-50 watts per pound as development proceeds. Space nuclear reactors in the megawatt range will provide even better power densities.

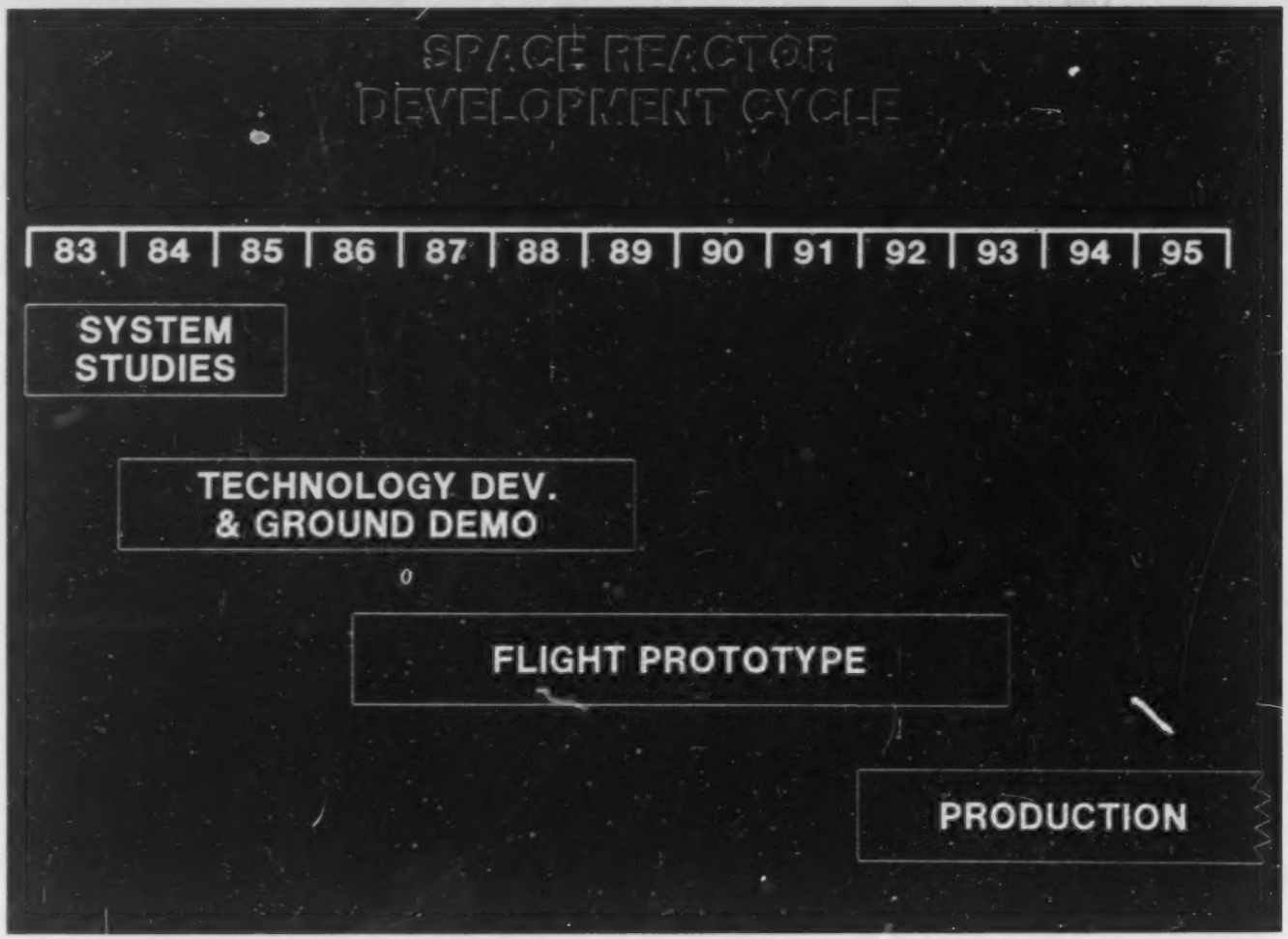
The need is clearly emerging and the technology to support the production of a space nuclear power system is available today. No new breakthrough is required. The technology, however, will require detailed and careful development and application engineering to ensure the effective transition to space. This work will emphasize heat transfer and power conversion; radiator design; high-temperature materials; and the

design of the reactor and shield configuration.

CHART NO. 3--REACTOR DEVELOPMENT CYCLE

Chart 3 indicates the major schedule phases of advanced space nuclear power development starting from a present technology base. The systems studies already underway should be concluded before 1985. The technology development is ready to be started this year and should follow through with ground demonstration as soon as possible. As this critical phase progresses, inputs will be obtained that will allow the start of construction of a flight prototype. In my estimation, it will take approximately a decade to complete the development of a safe space nuclear reactor. This then dictates that we must start now on the technology development phase if we are to achieve results and meet the projected missions of the early 90s shown on the previous charts.

Obviously, there is public concern over the safe reentry of a space nuclear reactor into the earth's atmosphere. A few years ago the United Nations formally addressed that issue. The report of a working group of technical experts from the United States and other nations, convened in 1979 to study and advise the UN Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space stated, "Nuclear power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TECHNOLOGY DEV.
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FLIGHT PROTOTYPE
PRODUCTION

sources can be used safely in space provided all necessary safety requirements are met." The U. S. position, presented in 1980 to the UN required launching an appropriately shielded reactor in a sub-critical mode; designs which would prevent criticality in the event of a launch abort or premature reentry; and limitation to start-up until the system achieved an orbit of sufficient duration to provide for fission product decay.

Since 1961, the United States has launched 22 nuclear isotope power systems and one experimental reactor without any safety incidents. In the three cases where the primary missions were aborted for different reasons, the isotope systems posed no danger to the environment because of sound design practices.

GE has been involved in nuclear power development for over 35 years. In the 1950s, we designed and developed a number of special-purpose reactors and in the 60s began work on a space nuclear reactor under contract to the previous Atomic Energy Commission.

We have flown nuclear power devices of the isotope variety on spacecraft and have dealt with their safety issues. We provided isotope generators for two communication satellites, LES 8 and 9, which have had

to date seven years of flawless power service and, of course, the Voyager deep space probes had phenomenal success and were powered by isotope systems which we supplied. Currently, we are providing nuclear power sources for the Solar Polar mission and will provide them for the Galileo scientific spacecraft.

These isotope systems, which are radioactive at launch, have successfully met launch and orbital safety requirements through containment techniques which have been proven through rigorous and thorough test programs. Reactors for space application, on the other hand, will not be radioactive at launch and will not be capable of activation--even in the event of launch abort.

With the successful acquisition of orbit or planetary trajectory, the reactor can then be activated with no terrestrial hazard.* Higher orbits with lifetimes of 300 years or more and planetary probes offer no hazard over the entire mission life because of the natural decay of the radioactive products during the orbit lifetime.

In the case of lower earth orbits, there are means to raise the orbit after use, to a long-term orbit. In addition, specific design of the reactor to allow breakup, burnup, and dispersion to safe levels--in the

event of reentry--is possible.

Radiation environments with proper shielding at the payload can be significantly less than the levels experienced from solar flares and the normal space environment and thus will not create a new source of severe radiation in space.

The checks and balances used to date in the application of nuclear devices in space have been very thorough and effective. Planning for similar safety programs has already been initiated even at this early stage. While I see the issue of public safety as manageable, obviously we must never permit any major risks and must exercise continuous vigilance, require very stringent design criteria and an extensive testing program.

Today, we have a large community of expertise in national laboratories and industry to perform this work. The majority of these professionals have two and three decades of space nuclear experience to draw upon. They represent a national resource which can and should be utilized for the development of this program. At the same time, we must recognize that this expertise will disappear unless new, young talent is brought into this arena through challenging bright young people to participate in this technology which is embodied in programs such as the SP 100.

The joint working committee which led to formation of a tri-agency organization to initiate a space nuclear power program deserves the full and continuing support of the subcommittees and the full Congress. This organization is performing a careful evaluation of the task and the front-end planning which is so indispensible to a successful program. The right steps are being taken at the right time, and I am confident the evaluation and planning process will result in continued support and eventual success.

I see the current plans and specifically the SP 100 program, as providing our nation with the ability to maintain a technological leadership in space without which we will soon lack the capability to perform the missions required in the next decade.

Since technologies have advanced dramatically in the last 10-15 years, particularly in the nuclear area as it would apply to a practical space power system, I would like to introduce Dr. Bertram Wolfe who has addressed you a number of times in the past and who will address the issues of nuclear technologies today.

DR. BERTRAM WOLFE

Thank you, Al.

Chairman Lloyd, Chairman Volkmer, Members of the Committee, I am Dr. Bertram Wolfe, Vice President of the General Electric Company and General Manager of the Nuclear Fuel and Special Projects Division. I am pleased to have this opportunity to appear before you to provide you with a positive appraisal of the present state of development of nuclear reactors which can be applied in meeting future space power needs.

As you know, the development of nuclear power in this country has a long history of accomplishments. General Electric is proud to have been a part of the development of this industry for over 35 years having designed, built, and tested nuclear power plants for aircraft, naval as well as commercial applications. We have also played a key role in the development of the SNAP series of space power plants. Our commercial reactor programs were initiated in the mid-fifties, with the development of the Boiling Water Reactor. BWRs now provide industrial, clean, safe, and reliable power all over the world.

The application of nuclear power in space encounters a unique challenge--how to reject the waste heat to the vacuum of space without large radiator structures. The answer lies in operating the power supply at the highest reasonable temperatures and minimizing the necessary

radiating surfaces. Fast spectrum reactors alone are able to accommodate the necessary high-temperature metals. The use of liquid metals is easily the most effective method of cooling the reactor and driving the heat-to-electricity conversion system. Fast spectrum liquid metal cooled reactor power supplies using refractory metals provide the most direct path to a useful space power source.

The use of liquid metal coolants in power plants was undertaken in the late 1940s for the Navy's nuclear-powered submarine Seawolf, at General Electric's Knolls Atomic Power Laboratory. General Electric, other firms, and the National Laboratories in conjunction with the Department of Energy, have been involved in the development of the fast spectrum reactor, its physics, core chemistry, high-temperature materials, heat transfer, controls, and fuels since the mid-50s. SEFOR, the Southwest Experimental Fast Oxide Reactor, designed and operated by GE in the 1960s, demonstrated fast spectrum reactor control and safety. Fast spectrum reactor technology has been brought together in the design and operation of the Experimental Breeder Reactor, EBR-II, and the Fast Flux Test Facility Reactor, FFTF, at the Idaho and Hanford sites, and most recently in the Clinch River Breeder Reactor and other plant designs under our nation's Liquid Metal Fast Breeder Reactor program.

Over the past two decades, an extensive data base has been developed for fast reactor fuel, fuel assemblies, liquid metal heat transfer system and reactor structure under the LMFBR program. The technical disciplines for understanding the basic mechanisms for providing reliable and safe nuclear reactor components are in place. Key facilities for component testing exist at National Laboratory sites. Irradiation testing of fuel components at EBR-II and the Fast Flux Test Facility can provide the environment for qualification testing of performance features of the space reactor fuel and structures. Critical experiment facilities exist at the Argonne, Idaho facility for sizing the constituent material of the reactor for adequate power output and control margins. Numerous liquid metal testing facilities exist at National Laboratories and participating industry facilities to qualify the heat transfer systems.

The LMFBR program has provided the knowledge base for predicting material behavior and setting specifications for meeting space reactor system requirements. The radiation damage envelope of structural components for the space reactor is well within the damage envelope of structural components used for LMFBRs. The candidate fuel and control materials for space reactor systems are nearly identical to LMFBR fuels

and similar core designs are likely such that the design tools require only minor modifications. Compatibility issues between the uranium fuel, fission products, structural materials, and liquid metal coolants have become more clearly focused since previous space reactor work in the 60s. The fabricability of the uranium fuel form will involve no new process development. For UO_2 fuel, a large manufacturing capability exists already.

The analytical tools developed and in use on the LMFBR program include structural codes, reliability codes, core design codes, chemical and thermal transport models and fast reactor neutronic codes. These codes, for the most part, can be used with but minor modifications on the space reactor program.

As I pointed out earlier, significant departure from the LMFBR program technology is the higher reactor coolant outlet temperature needed to maximize power conversion efficiencies and reduce overall system weight. This higher temperature requires the use of refractory alloys made from metals such as Molybdenum, Tungsten, Rhenium, Niobium, or Tantalum rather than more conventional steels. Although refractory metals have been in use in this country for some time, their availability

and fabrication techniques must be improved. In addition, the satisfactory performance of these alloys in high radiation environments requires further confirmation.

In summation, we at GE have concluded that the country possesses the technology here for a successful space reactor power supply program. High-temperature metal production and testing need particular attention. Other than that, the liquid metal cooled faster reactor programs of the last decade provide a sound foundation. All that is needed is a commitment. Thank you.

ALLAN J. ROSENBERG

Vice President, General Electric Company
General Manager, Space Systems Division

PRESENT POSITION: Mr. Rosenberg is responsible for the general management of Space Systems Division, which numbers 7200 people nationally, 3700 of whom are located in King of Prussia, Pennsylvania, the site of the Division Headquarters. Space Systems Division has a diverse range of high technology products and services organized into three operating components: Spacecraft Operations, Military and Data Systems Operations, and Re-entry Systems Operations. The Division is a contractor to numerous government agencies for such products as communication satellites, earth observation satellites, large scale data systems and strategic ballistic re-entry systems. In addition to King of Prussia, Space Systems Division has facilities in Philadelphia, Pennsylvania; Sunnyvale, California; Houston, Texas; Huntsville, Alabama; Bedford, Massachusetts; several locations in the Washington, D.C. area and field site personnel across the country.

EDUCATION: BSEE, Brown University, 1948

PREVIOUS ASSIGNMENT: Prior to assuming his present position with Space Systems Division, Mr. Rosenberg was General Manager-Aerospace Instruments and Electrical Systems Department in Wilmington, Massachusetts from 1974 to April 1980, where he was responsible for a key part of the aircraft equipment business covering such products as cockpit displays, fuel management systems, engine sensors, flight reference systems, and electrical generating systems.

EARLIER GENERAL ELECTRIC CO. EXPERIENCE: Mr. Rosenberg joined General Electric Company in 1948. After holding various engineering positions at GE's Thomson Laboratory in Lynn, Massachusetts, he transferred to the Aircraft Accessory Turbine Department where he held several managerial positions including Manager-Aircraft Accessory Turbine Laboratory, Manager-Production Engineering Accessory Products and Manager-Manufacturing for Aircraft Controls and Accessories. In 1966, he became Manager-Quality Control for the Small Aircraft Engine Department.

In 1967 he was named Manager-Manufacturing of the Aircraft Equipment Division's Armament Department in Burlington, Vermont and later became General Manager of that Department. In 1971, he transferred to the Aircraft Engine Group to become Manager-Lynn Manufacturing, directing their manufacturing resources at five locations. In 1974 he was appointed Manager-Aerospace Instruments and Product Support and was assigned the additional responsibilities for Electrical Systems in 1978.

SOCIETIES: Licensed Professional Engineer, Massachusetts, since 1953. Associate Director-Armed Forces Communications and Electronics Association. Member Board of Governors-National Space Club.

HONORS: Degree Magna Cum Laude, Sigma XI, Tau Beta Pi
American Welding Society, N.E. District, Meritorious Service Award

BIOGRAPHY

OF

DR. BERTRAM WOLFE

Dr. Wolfe received his B.A. in Physics from Princeton University in 1950 and his Ph.D. from Cornell University in 1954. He has been in the nuclear energy field since 1955, working all but two years at General Electric. Dr. Wolfe has worked in almost all phases of nuclear energy from reactor design to development of new reactor concepts, and is presently General Manager of Nuclear Fuel and Special Projects Division of General Electric responsible for the nuclear fuel cycle and the design and development of advanced reactor systems. Dr. Wolfe is a Vice President of General Electric Company and a member of the Board of Directors of the Atomic Industrial Forum and the American Nuclear Energy Council. He is a Fellow of the American Nuclear Society, a Professional Engineer in the State of California, and a member of the National Academy of Engineering. He holds a half dozen patents in the nuclear field and is the author of several dozen publications concerning nuclear energy technology and energy in general.

Mrs. LLOYD. Thank you, Mr. Rosenberg.
Dr. Wolfe, it's now your turn.

STATEMENT BY DR. BERTRAM WOLFE, VICE PRESIDENT, GENERAL ELECTRIC CO., AND GENERAL MANAGER, NUCLEAR FUEL AND SPECIAL PROJECTS DIVISION

Dr. WOLFE. I'll try to summarize my statements since you're going to put the complete written statement in the record.

Mrs. LLOYD. It will all be made part of the record.

Dr. WOLFE. I'll leave out the experience of General Electric which, of course, is very wide in the nuclear business, and I'll leave out our great desire to participate on this program.

We believe that we can answer positively your desire to get an answer as to whether we can put a reactor in space in a reasonable amount of time in a reliable fashion. We believe we can. We believe that the major problem that faces us today, in putting a high power source in space, is the high temperature required in order to keep the size of the radiator small, and also the desire to keep the size of the reactor itself small in size and weight. We believe the answer lies in relying on liquid-metal-cooled fast reactors in which we, and the country as a whole, have a large amount of applicable experience, starting some 30 years ago with the Sea Wolf and working up through the present fast reactor program, some of which you've heard about here. We believe that all of the nuclear technology, configuration technology, codes, and analytical techniques—safety and so on—that have been used in the fast reactor program are applicable to the use of fast spectrum liquid-metal-cooled reactors in space.

We think the major problem lies in raising the temperature of these reactors. This would require, as Dr. Harms mentioned, the use of refractory metals. We think the major new development programs or extension of old development programs required is, in fact, the development of those refractory metals so that they can be reliably produced. Then they must be tested and shown that they will last over the mission lifetime. With the development of those materials, and the marriage of those materials with the physics and analytical techniques of the fast reactor program, we believe as I noted, that we could put up a reliable power source in the tens to hundreds of kilowatt range in the next 7 to 10 years. We think that what's required as much as the high temperature material is the commitment of the nation and the Congress and with that commitment we believe that the mission could be accomplished.

Thank you very much.

Mrs. LLOYD. Thank you, Dr. Wolfe.

Dr. Dahlberg, please proceed with your testimony.

STATEMENT BY DR. RICHARD DAHLBERG, DIRECTOR OF SPACE NUCLEAR POWER, GA TECHNOLOGIES, INC.

Dr. DAHLBERG. My name is Richard Dahlberg, director of space nuclear power at GA Technologies. I appreciate the opportunity to provide the members and staff of your subcommittee with information concerning GA's participation in the space nuclear power program.

These oral remarks are a condensation of key elements from a booklet which we prepared for the subcommittee, a draft copy of which is before you.

Mrs. LLOYD. We appreciate the copy.

Dr. DAHLBERG. GA Technologies, formerly General Atomic, was organized in 1955 for the express purpose of developing peaceful applications of nuclear energy. We have been developing nuclear power systems and supporting technologies as our primary business pursuit for 28 years. GA is a world leader in the development of high-temperature gas-cooled reactors, fusion power reactors, fail-safe nuclear research reactors, and space nuclear power technologies.

The emerging needs for power in space for exploration, scientific study, industrial processes and national defense indicate that nuclear power is the enabling technology; and several people have already commented on that point. The needs appear to be well beyond the energy requirements available from conventional solar energy cells.

Recognizing that mission definition will determine power requirements, and also the appropriate technology, it still appears that space nuclear power development is essential for progress.

For perspective, it is essential that we recognize the enormous effort that was devoted to space nuclear power development prior to 1973. The current programs should build on the achievements of those early efforts. GA played a major role in space nuclear power development from 1958 to 1973. The technology developed during that period has been augmented since then at GA with experience in advanced gas-cooled reactor, fusion research, energy conversion technology and extended-life nuclear fuels. A summary of this experience is shown on this first chart.

As you can see GA has been involved in many space power technologies. Nuclear power for rockets, thermionics, thermoelectrics, heat pipe cooled reactors, long life fuel, thermophotovoltaic technology, and gas cooled technology are all elements of our experience. Three of these programs are under consideration for continued funding as technology development activities under the SP-100 program. I propose now to cover some of this experience in a little more detail.

Nuclear rockets were a major activity at GA in the 1960's and early 1970's. For the NERVA program, GA manufactured the coated particle fuel which was the basis for the core design. That fuel technology, which was described briefly by Dr. Powell from Brookhaven, is currently the basis for the HTGR commercial reactor program and is in use at Fort St. Vrain reactor in Colorado. Coated particle fuel looks attractive for future space power applications, and I'll say just a little bit more about that in a few minutes.

One of the most successful GA space nuclear power developments is the thermionic reactor program initiated in the late sixties. Thermionic technology is based on the fact that electrons are easily boiled off from some materials, such as tungsten, when heated to high temperatures. These emitted electrons can be collected by a metal collector, and when incorporated in a properly designed system will result in an electrical current. A picture of a

thermionic cell is shown on chart 2. A similar cell made by GA is on display in the Smithsonian here in Washington.

The goal of the program at GA was a space power system in which electrical power was generated in the core by thermionic diodes. The program included the design, development, and incore testing of thermionic fuel elements, and power system design studies for power levels ranging from 5 kilowatts to 3 megawatts. The program was successful. Many fuel elements were fabricated and tested incore to lifetimes of 1 to 2 years.

One of the most attractive characteristics of the technology is the low inorbit mass and volume, a consequence of incore power conversion, and a small radiator because of the high heat rejection temperature. An indication of the low mass is shown on chart 4. The data shown here were developed during a DOE-sponsored program in January of this year; they show the power to mass ratio for a large number of space power systems. The horizontal axis is time, through the year 2000, and the data points indicate possible evolutionary improvements in the many technologies. The data point above all the other is a thermionic power system.

For many years, GA has been active in developing improved thermoelectric materials for space power applications and for designing and developing related space power systems. This technology has been used in space because of the high reliability of thermoelectric converters. Our work includes radioisotope fueled systems such as the 35 watt system for the Navy's transit navigational satellite launched in 1972. This power supply is still operational. We are currently under contract to JPL for high-efficiency high-temperature thermoelectric materials.

One of the simplest and most efficient means for transferring heat is through heat pipes. GA has been participating in development of the heat pipe reactor and associated thermoelectric power conversion systems with the Los Alamos National Laboratory, who have been the principal proponent of this technology. The concept is appealing because of its reliability and simplicity. Under contract to Los Alamos, GA developed an improved design to transfer heat from the heat pipe to the thermoelectric power conversion system. More recently, GA was under contract to DOE to investigate an alternative fuel/core design that involved the use of GA coated particle fuel technology.

The coated fuel particles developed for the hightemperature gas-cooled reactor are proving to have applications in several space power systems. This next slide is a scanning electron microscope picture of a broken coated fuel particle—the entire particle looks like a grain of sand. It's advantage is that it is dimensionally stable under irradiation and it retains all the fission products within the coatings. It's proving to be useful not only for the thermionic technology but for gas-cooling technology, NERVA technology, and the heat pipe reactor technology.

The HTGR and gas-cooled fast reactor programs have resulted in technology developments that are applicable to space nuclear power. GA has designed, manufactured and operated fuel and core components, primary system components, and complete gas reactor systems. The gascooled reactor with a Brayton cycle power conversion system is an option which can meet energy requirements from

tens of kilowatts to megawatts. Dr. Powell, from Brookhaven, gave you an example of a high-power application for the gas-cooled Brayton cycle.

GA is currently under contract to, JPL under the SP-100 program, to evaluate alternative space power systems. We will shortly make recommendations on the most suitable technologies for meeting a set of baseline requirements, recognizing that if requirements change as a result of mission analysis, the technology of choice may also change. We are teamed with Martin Marietta to bring their extensive space systems expertise to this program.

These remarks briefly cover what GA has been doing over the last 28 years in space nuclear power. We bring extensive expertise to the Nation's space power programs because we have been continuously active in nuclear power development and related space power technologies.

This expertise, along with that of other industrial contractors and government laboratories, is being effectively coordinated through the SP-100 program recently established through the Memorandum of Understanding between DOE, NASA and DOD/DARPA. The organization has been described by others and I won't go into that.

Nor will I comment on the list of requirements emerging through mission analysis for space nuclear power in the 100 kilowatt to megawatt range. There are many technologies of potential interest to meet these requirements. We have chosen to categorize these by the power conversion system, of which five appear to be of major interest. These are shown on the next two charts. One can associate various heat transfer and reactor subsystems with these power conversion subsystems to form an overall power system. The number of power systems possible with these subsystem building blocks is very large, of course, but the ones I've shown here appear to be the ones that have the greatest potential for meeting user requirements.

GA Technology, as I indicated previously, has background and expertise in most of the systems shown. The system of choice will depend on user requirements and the development time available to bring the most promising technologies to a state of readiness.

The final point I want to make is that there are technology programs that should be pursued now because they are essentially generic; that is, they will benefit many, if not all, of the systems we've just seen. The SP-100 program managers have recognized the need to pursue generic technology programs; however, funding has limited progress to date and should be substantially increased to avoid adverse impact to the overall program.

To give more perspective to this point, chart 9 shows some of these needs. All of the concepts will need improved nuclear fuels to meet lifetime and efficiency requirements. Improved materials are necessary for the higher temperatures that will result in low on-station mass and volume; these points have been well stated by others.

In summary, GA has extensive background and expertise in the entire spectrum of space nuclear power technologies. We have retained our space power team even though the Government has been relatively inactive in the space nuclear power arena since

1973. We are anxious to bring this expertise to bear on emerging needs, both commercial and defense. We believe that the SP-100 program will be an effective channel for serving these needs if adequate funds are provided.

Thank you very much.

[The prepared statement of Dr. Dahlberg, plus presentation booklet mentioned, to be included in the record, follow:]

STATEMENT BEFORE THE

SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

COMMITTEE ON SCIENCE AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

MAY 24, 1983

SPACE NUCLEAR POWER

DR. RICHARD C. DAHLBERG
DIRECTOR, SPACE POWER PROGRAM
GA TECHNOLOGIES INC.
SAN DIEGO, CALIFORNIA

Madame Chairman and Members of the Subcommittee:

My name is Richard Dahlberg, Director, Space Nuclear Power at GA Technologies, Inc. in San Diego, California. I appreciate the opportunity to provide the members and staff of your committee with information concerning GA's participation in the Space Nuclear Power Program.

These oral remarks are a condensation of the key elements from a presentation booklet we prepared for the subcommittee which I would ask be made a part of the record.

GA Technologies, formerly General Atomic Company, was organized in 1955 for the express purpose of developing peaceful applications of nuclear energy. We have been developing nuclear power systems and supporting technologies as our primary business pursuit for 28 years. GA is a world leader in development of high-temperature gas-cooled reactors, fusion power reactors, fail-safe nuclear research reactors, and, space nuclear power technologies.

The emerging needs for power in space that are required for exploration, scientific study, industrial processes and national defense indicate that nuclear power is the enabling technology, with projected energy requirements well beyond the limits of solar energy cells. Design parameters for many space systems have been constrained by limits on the power that could be provided. These constraints complicate system developments by restricting some

mission objectives and increasing development costs. Recognizing that mission definition will determine power requirements, and thereby the appropriate technology, it still appears that space nuclear power development is essential for progress.

For perspective, it is essential that we recognize the enormous effort that was devoted to space nuclear power development prior to 1973 when the United States development programs were terminated. The current programs should build on the achievements of those early efforts to most effectively develop power systems that will enable accomplishment of today's mission requirements. GA played a major role in space nuclear power development from 1958 to 1973. The technology developed during that period has been augmented by subsequent GA experience in advanced gas-cooled reactors, fusion research, energy conversion technology and extended-life nuclear fuels. A summary of this experience is shown on Chart 1.

As you can see, GA has been involved in many space power development areas. Nuclear power for rockets, thermionics, thermoelectrics, heat pipe cooled reactors, long life fuel, thermophotovoltaic technology, and gas cooled technology are all elements of our experience. Three of these programs are under consideration for continued funding as technology development activities under the SP-100 program. I propose now to cover some of this experience in a little more detail.

Nuclear rockets were a major activity at GA in the 1960s and early 1970s. For the NERVA program, GA manufactured the coated

particle fuel which was the basis for the core design. That fuel technology is also the basis for the HTGR program and is currently in commercial use in the Fort St. Vrain reactor in Colorado. Coated particle fuel looks attractive for future space power applications, but I'll have more to say about that in a few minutes. GA also was the developer of a core and reactor for rocket applications, or more accurately for space transportation. This program used separated tungsten as the core structural material, with gas cooling in an open cycle as the propulsion mechanism.

One of the most successful GA space nuclear power developments is the thermionic reactor program initiated in the late sixties. Thermionic technology is based on the fact that electrons are easily "boiled off" from some materials, such as tungsten, when heated to high temperatures. These emitted electrons can be collected by a metal collector, and when incorporated in a properly designed system will result in an electrical current. A picture of a thermionic cell is shown on Chart 2. A similar cell made by GA is on display in the Smithsonian here in Washington.

The goal of the program at GA was a space power system in which electrical power was generated in the core by thermionic diodes. The program included the design, development, and in-core testing of thermionic fuel elements, power system design studies for power levels ranging from 5 kW(e) to 3 MW(e), reactor critical experiments, and the design and cost estimate of a thermionic reactor experient. The program was successful. Many fuel elements were fabricated and tested in-core to lifetimes of 1 to 2 years. Power systems were designed which still appear to be extremely attractive

for space applications from the 100 kW(e) into the megawatt range. A thermionic reactor is shown on Chart 3. Attractive characteristics include low in-orbit mass and volume, a consequence of in-core power conversion, and a small radiator because of the high heat rejection temperature. An indication of the low mass is shown on Chart 4. The data shown here were developed during a DOE sponsored program in January of this year and show the power to mass ratio for a large number of space nuclear power systems. The horizontal axis is time, through the year 2000, and the data points also indicate evolutionary improvements in the many technologies. The data point above all the others is a thermionic power system.

For many years, GA has been active in developing improved thermoelectric materials for space power applications and for designing and developing related space power systems. This technology has been widely used in space because of the high reliability of thermoelectric converters. Our work includes radioisotope fueled systems such as the 35 watt system for the Navy's transit navigational satellite launched in 1972. Data indicates that this power supply is still operational. We have also continued work on thermoelectric materials and are currently involved in an Army program to develop an improved fossil-fueled thermoelectric converter for terrestrial mobile electric power generators.

One of the simplest and most efficient means for transferring heat is through heat pipes. GA has been participating in development of the heat pipe reactor and associated thermoelectric power

conversion system. The Los Alamos National Laboratory has been the principal proponent of this technology. The concept is appealing because of its reliability and simplicity. Under contract to Los Alamos, GA developed an improved design to transfer heat from the heat pipe to the thermoelectric power conversion system. More recently, GA was under contract to DOE to investigate an alternative fuel/core design that involved the use of GA coated particle fuel technology.

The coated fuel particles developed for the high-temperature gas-cooled reactor are proving to have application in several space power systems. An electron microscope picture (Chart 5) of a coated particle broken to expose the uranium kernel shows several layers of unique coatings. These coated particles are dimensionally stable even after extensive irradiation, a property that makes them the most attractive long-life fuels for use in heat pipe reactors, in-core thermionics reactors and open-cycle gas cooled reactors. Over the past 20 years, GA has developed and manufactured over 50,000 kilograms of coated fuel particles for use in the NERVA and UHTREX programs and for two HTGR power plants, Peach Bottom and Fort St. Vrain.

The HTGR and gas-cooled fast reactor programs have resulted in technology developments that are applicable to space nuclear power. GA has designed, manufactured and operated fuel and core components, primary system components, and complete gas reactor systems. The gas-cooled reactor with a Brayton cycle power conversion system is an option which can meet energy requirements from

tens of kilowatts to megawatts. A gas-cooled particle bed reactor concept with an open Brayton cycle power converter, under development at Brookhaven National Laboratory, appears to be capable of several megawatts output in a steady state mode, and over 100 megawatts in a pulsing mode. This is shown on Chart 6.

GA is currently under contract to JPL, under the SP-100 program, to evaluate alternative space power systems. We will shortly make recommendations on the most suitable technologies in meeting a set of baseline requirements, recognizing that if requirements change as a result of mission analysis, the technology of choice may also change. We are teamed with Martin Marietta to focus their extensive space systems expertise on this program. This GA-Martin Marietta team is also competing for a multi-megawatt power study sponsored by the NASA-Lewis Laboratory.

These remarks briefly cover what GA has been doing over the last 28 years in space nuclear power. We bring extensive expertise to the nation's space power programs because we have been continuously active in nuclear power development and related space power technologies.

This expertise, along with that of other industrial contractors and government laboratories, is being effectively coordinated through the SP-100 program recently established through the Memorandum of Understanding between DOE, NASA and DOD/DARPA. The SP-100 organization has been described by others and I won't go into that.

Nor will I comment on the list of requirements emerging through mission analysis for space nuclear power in the 100 kW to megawatt range, other than to note that this is an extremely important process - to assure that the technical work in progress will be responsive to user requirements. It is essential to a continuing sensible program.

There are many technologies of potential interest for space nuclear power. We have chosen to categorize these by the power conversion system, of which five appear to be of major interest. These are shown on the next two charts, 7 and 8. One can associate various heat transfer and reactor subsystems with these power conversion subsystems to form an overall power system. The number of power systems possible with these subsystem building blocks is very large, of course, but the ones I've shown are those which appear to have the greatest potential for meeting user requirements. GA Technologies, as I indicated previously, has background and expertise in most of the systems shown. The system of choice will depend on user missions and requirements, and the development time available to bring the most promising technologies to a state of readiness.

The final point I want to make is that there are technology programs that should be pursued now because they are essentially generic; that is, they will benefit many, if not all, of the systems we've just seen. The SP-100 program managers have recognized the need to pursue generic technology programs; however, funding has limited progress and should be substantially increased to avoid

adverse impact to the overall program.

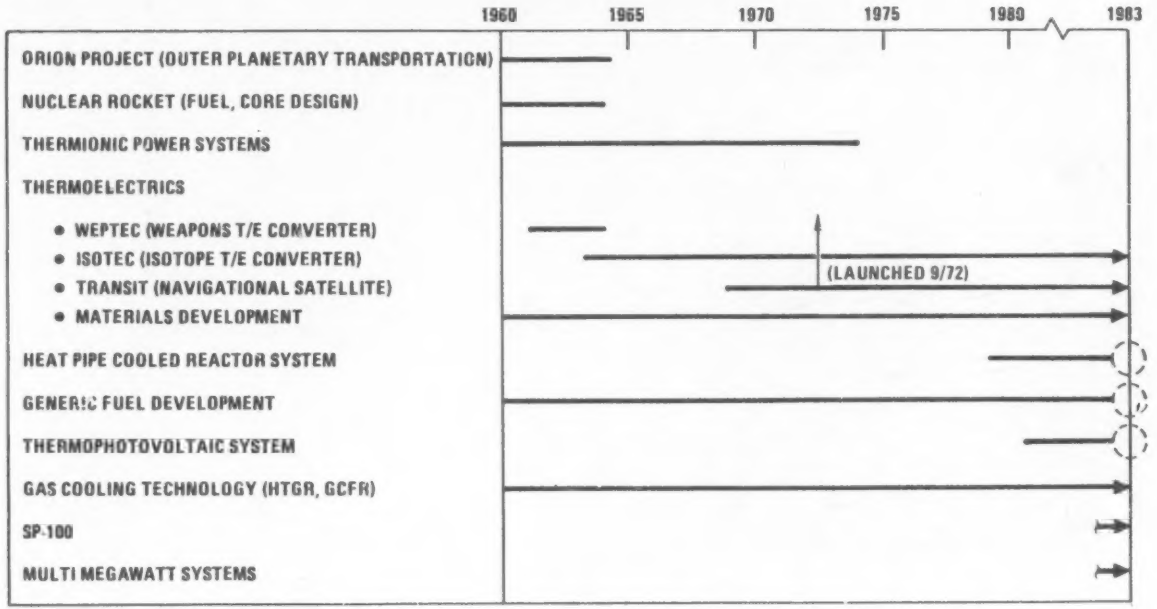
To give more perspective to this point, Chart 9 shows some of these needs. All concepts will need improved nuclear fuels to meet lifetime and efficiency requirements. Improved materials are necessary for the higher temperatures that will result in low on-station mass and volume. Similar comments can be made with respect to the other items on the chart.

In summary, GA has extensive background and expertise in the entire spectrum of space nuclear power technologies. We have retained our space power team even though the government has been relatively inactive in the space nuclear power arena since 1973. We are anxious to bring this expertise to bear on emerging needs, both commercial and defense. We believe that the SP-100 program will be an effective channel for serving these needs if adequate funds are provided.

Thank you for this opportunity to share our views with you.

GA Technologies

CHART 1
GA SPACE NUCLEAR POWER PROGRAMS
CURRENT STATUS

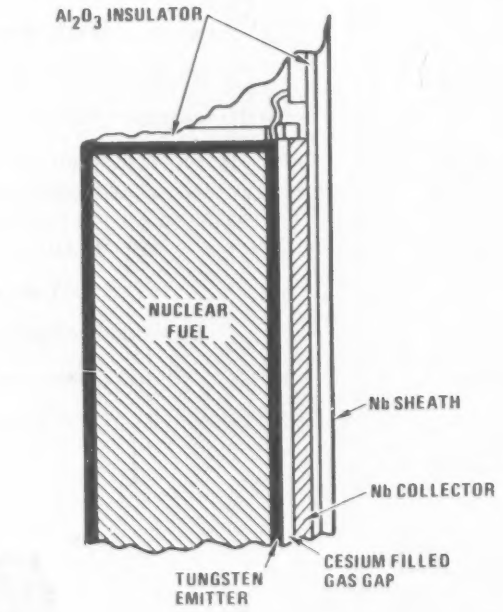


PROGRAM CONTINUATION UNDER CONSIDERATION

G-287(8)

GA Technologies

CHART 2
THERMIONIC CELL



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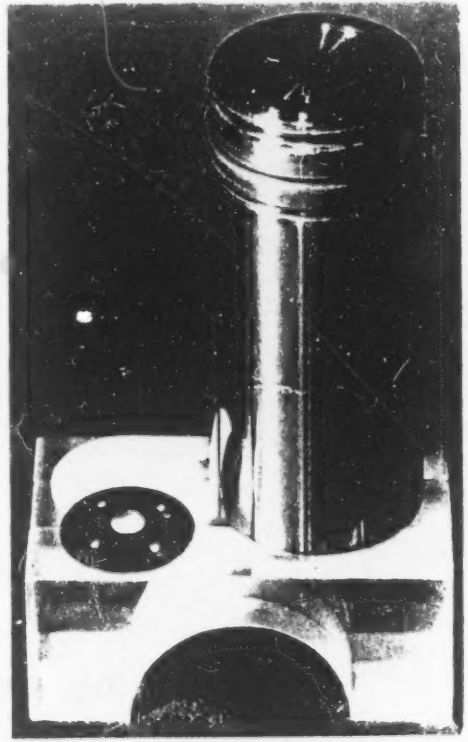

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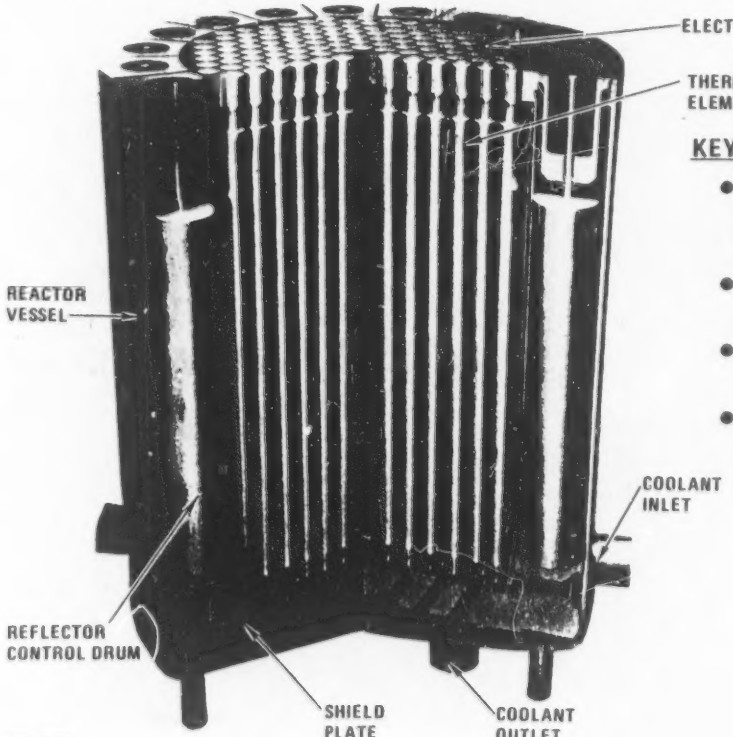
GA Technologies

CHART 3
IN-CORE THERMIONICS – A GA TECHNOLOGY

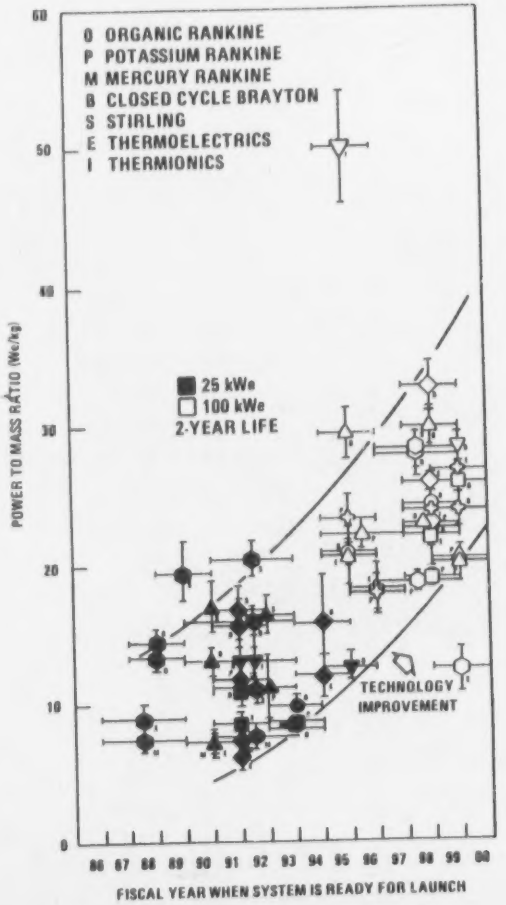


KEY FEATURES – DEMONSTRATED

- THERMIONIC FUEL ELEMENTS PRODUCE ELECTRIC POWER DENSITY IN REACTOR CORE
- REDUNDANT STATIC POWER CONVERSION
- LOW MASS/VOLUME (DUE TO SMALL RADIATOR)
- SCALABLE TO HIGH POWER (MULTI-MEGAWATT)

GA Technologies

CHART 4
COMPARATIVE EVALUATION
POWER TO MASS RATIO



SOURCE: ROCKWELL INTERNATIONAL
STUDY – "SPACE REACTOR
ELECTRIC SYSTEMS"
29 MARCH 1983

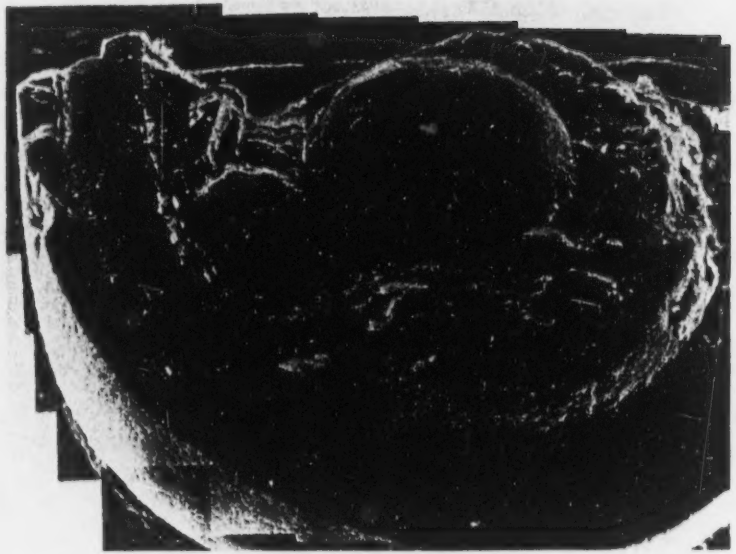
G-299(7)

GA Technologies

CHART 5
HTGR FUEL = FUEL FOR SPACE POWER

COATED PARTICLES:

- **APPLICABLE TO SEVERAL SPACE NUCLEAR POWER CONCEPTS**
- **PARTICLES SHOW NO SWELLING WITH BURNUP**



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GA Technologies

CHART 6
OPEN BRAYTON CYCLE (FIXED BED REACTOR) SYSTEM

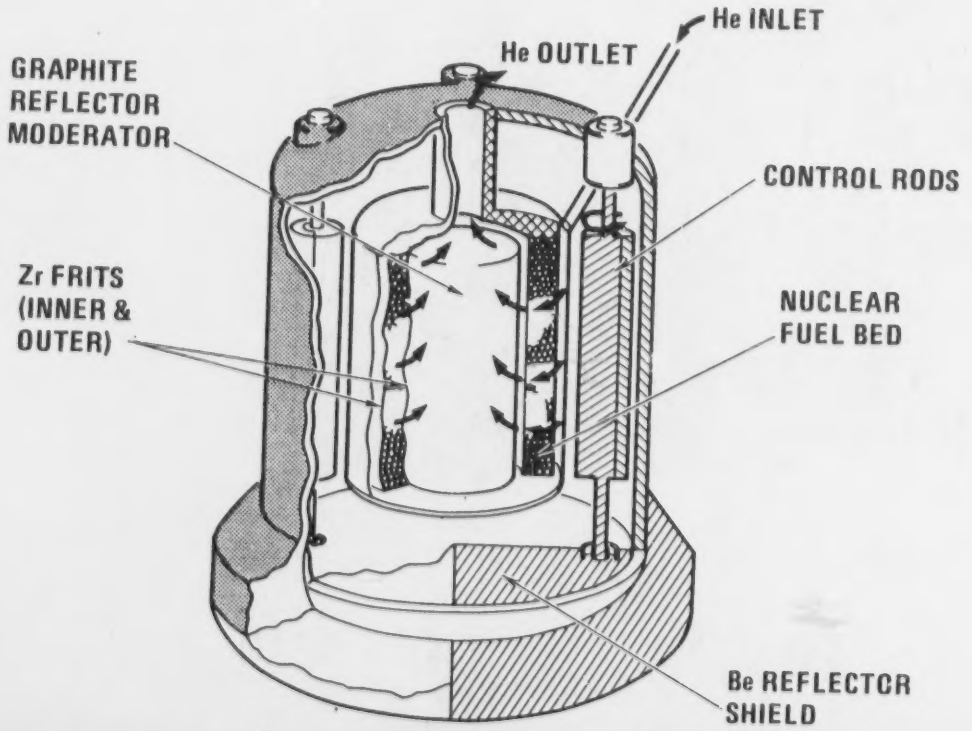

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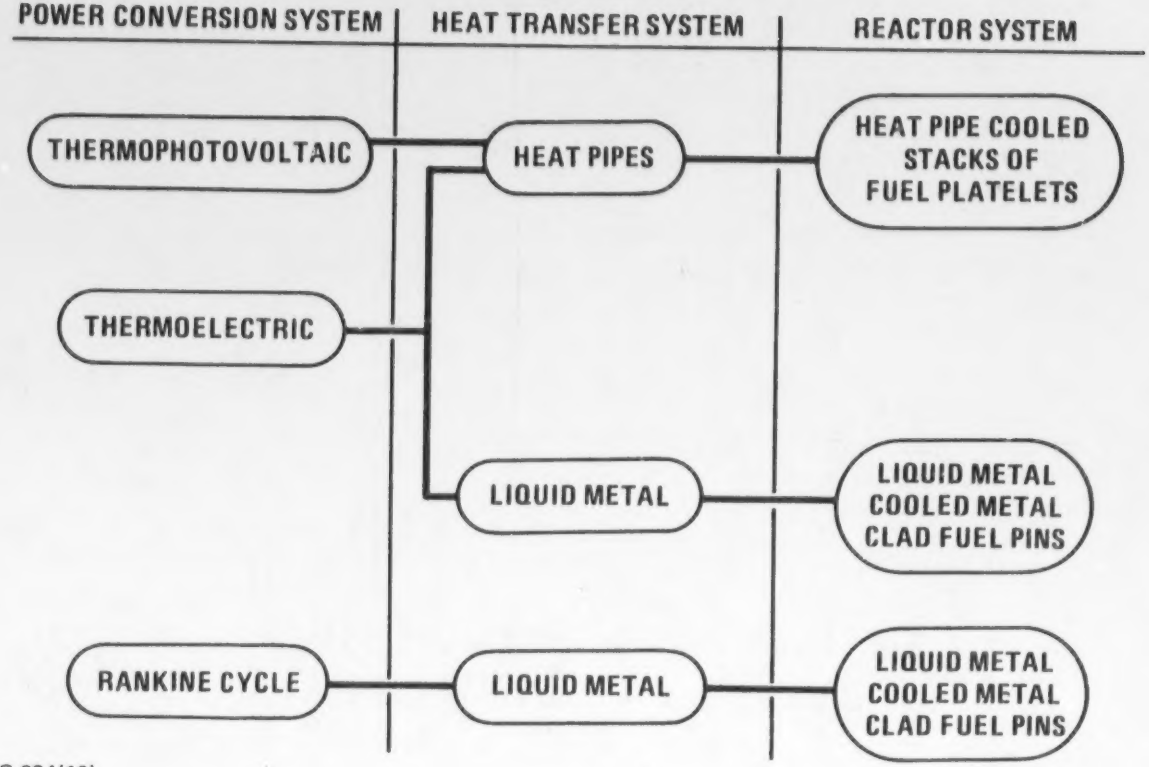
CHART 7

ROAD MAP TO ALTERNATIVE SPACE NUCLEAR POWER SYSTEMS



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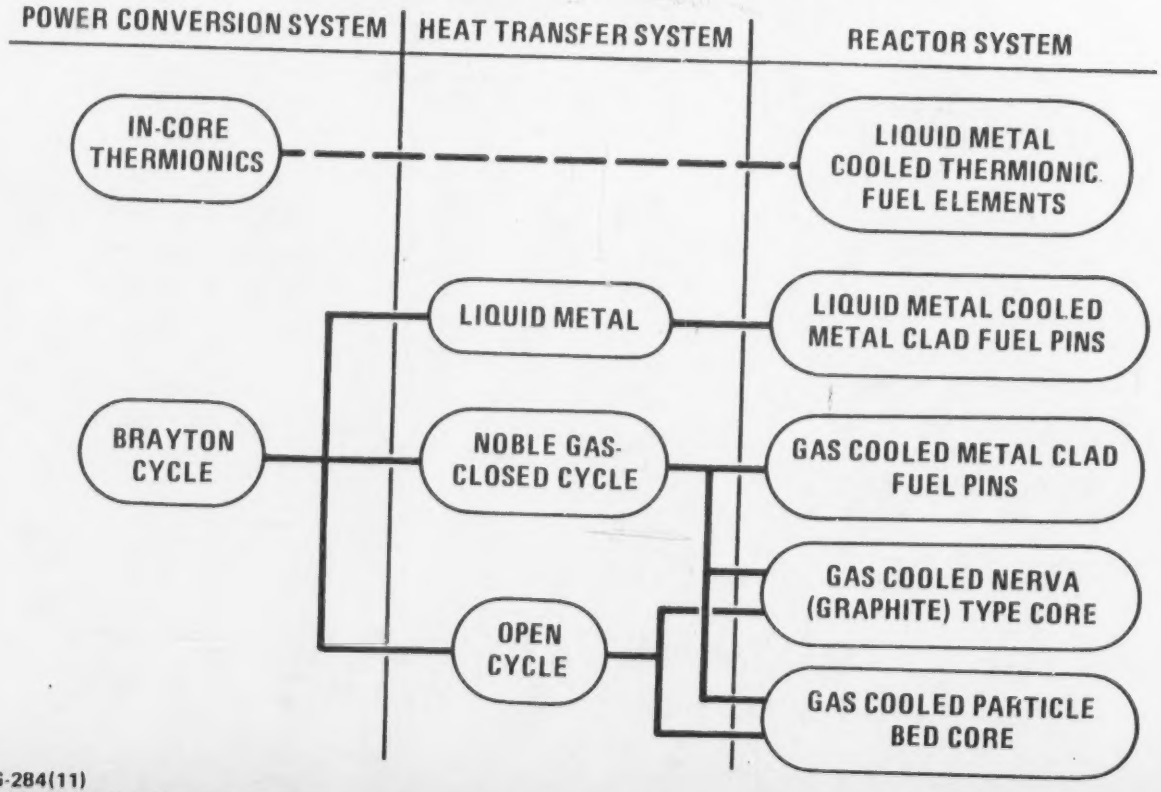
GA Technologies

CHART 8

ROAD MAP TO ALTERNATIVE SPACE NUCLEAR POWER SYSTEMS



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GA Technologies

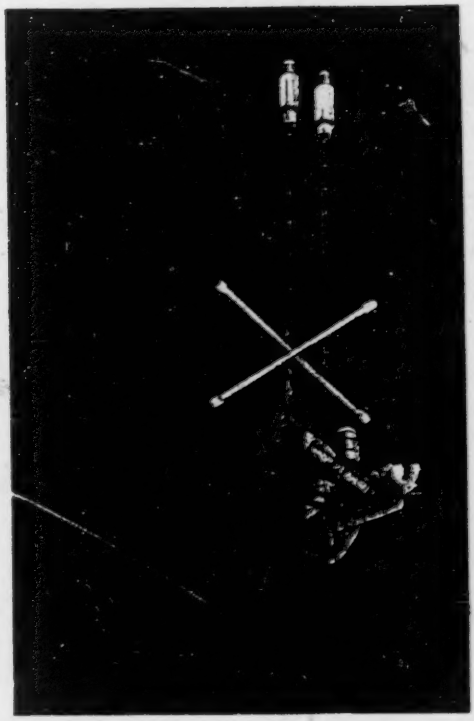
CHART 9
TECHNOLOGY BUILDING BLOCKS WILL PACE SYSTEMS DEVELOPMENT

TECHNOLOGY NEEDS	POWER CONVERSION TYPES					
	THERMIONIC	BRAYTON CYCLE		THERMO-ELECTRIC	RANKINE OR STIRLING/ CYCLE	THERMO-PHOTOVOLTAIC
		OPEN CYCLE	CLOSED CYCLE			
• IMPROVED NUCLEAR FUEL	✓	✓	✓	✓	✓	✓
• IMPROVED MATERIALS						
STRUCTURAL MATERIALS	✓	✓	✓	✓	✓	✓
INSULATORS	✓			✓		✓
REFRACTORY METALS	✓	✓	✓	✓	✓	✓
THERMOELECTRICS				✓		
• HEAT PIPES			✓	✓	✓	✓
• RADIATORS	✓		✓	✓	✓	✓

G-284(16)

SPACE NUCLEAR POWER
THE ENABLING TECHNOLOGY

A PERSPECTIVE BY
GA TECHNOLOGIES



G-284(19)

Presentation To: Subcommittee on Energy Research and Production
Committee on Science and Technology
House of Representatives

Presentation By: Dr. Richard C. Dahlberg
Director, Space Power Program
GA Technologies Inc.
San Diego, CA

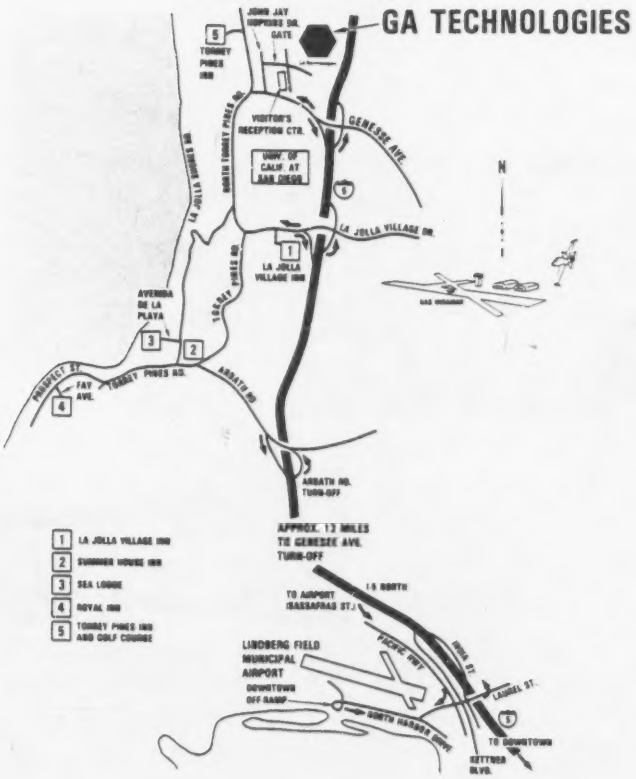
SPACE NUCLEAR POWER THE ENABLING TECHNOLOGY

Contents

- GA Technologies — An Introduction
- GA Space Nuclear Power Experience — Extensive
- Space Nuclear Power — An Emerging Need
- Current Status Space Nuclear Power Program
- Alternative Space Nuclear Power Systems — A Roadmap
- Summary

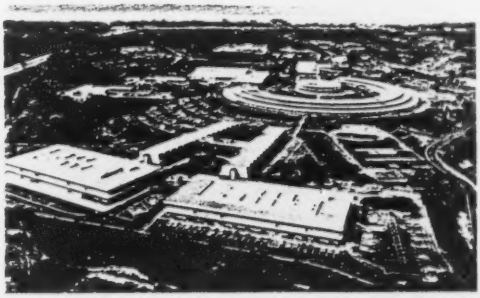
GA TECHNOLOGIES — AN INTRODUCTION

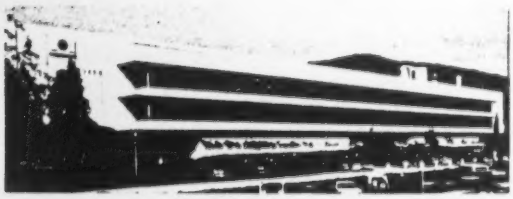
THE FOCAL POINT



GA Technologies Inc. (formerly General Atomic Company) is a wholly owned subsidiary of Gulf Oil Corporation located in the Northwest area of San Diego, California. For the past 28 years, GA has developed useful applications of nuclear power and is currently in the forefront of power technologies development for both fission and fusion reactors.

GA DEVELOPMENT LABORATORIES





ARE COMPLEMENTED WITH MAJOR MANUFACTURING FACILITIES

G 232114I

In 1958, General Dynamics completed an extensive and unique laboratory complex designed specifically for nuclear power research. They recruited a team of imminent scientists and engineers and equipped the laboratories with advanced research, design, fabrication and testing equipment. Later, additional facilities were constructed nearby in Sorrento Valley for testing prestressed concrete reactor vessels, experimentation in controlled fusion, directed energy research and for manufacture of nuclear power reactor fuels. The entire complex covers 350 acres and contains over one million square feet of office, laboratory and manufacturing space.

The potential for this company was quickly recognized and GA was purchased by Gulf Oil in 1967. In 1982 the name was changed from General Atomic Company to GA Technologies Inc.

GA Technologies Inc.

PERSONNEL

TOTAL STAFF	~1800
DEGREED STAFF	~ 900

REVENUES (1982)

TOTAL	$149 MILLION
PERCENT GOVERNMENT	50%
PERCENT PRIVATE	50%

G-242

Currently, GA is staffed with 1800 personnel of which about half are scientific and engineering professionals. There are many of the original staff still with GA and some 20% have been with the company more than 20 years. Of key importance is the fact that virtually all of those who were involved in space nuclear power research in the sixties and seventies are still at GA and are eager to resume their important contribution to this new frontier.

MAJOR PROGRAMS AT GA

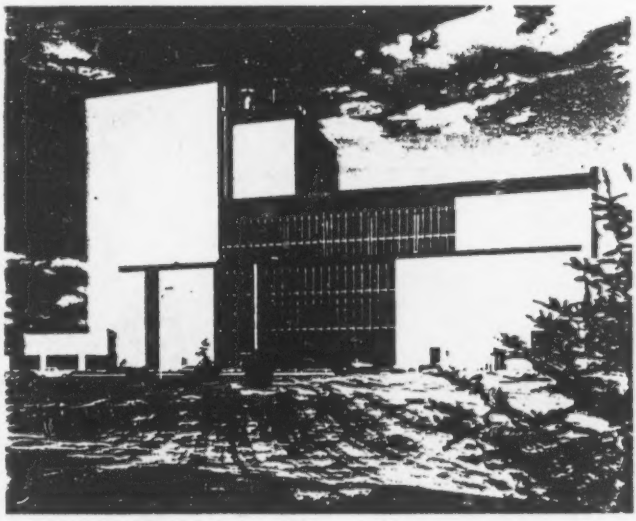
- DEFENSE PROGRAMS: RESEARCH, DEVELOPMENT, PRODUCTION AND SUPPORT
  - CHEMICAL WEAPONS DEMILITARIZATION SYSTEMS
  - THERMOELECTRIC POWER SYSTEMS
  - SPACE NUCLEAR POWER SYSTEMS
  - NUCLEAR DETECTION AND MEASUREMENT SYSTEMS
- ENGINEERING (HI TECH) SERVICES
- GAS COOLED REACTORS (FORT ST. VRAIN)
  - COATED FUEL PARTICLE TECHNOLOGY
- ELECTRONIC EQUIPMENT (MANUFACTURING)
- FUSION R&D, ENGINEERING AND TESTING
- TRIGA RESEARCH AND POWER REACTORS
- ADVANCED MATERIALS AND PROCESSES R&D

G-284(30)

Research, development, and manufacturing activities at GA can be grouped into seven major areas. We are currently expanding our contribution to Defense R & D. Key current programs include development of chemical weapons demilitartization systems for economical and environmentally clean disposal of the huge obsolete weapons stockpile. We are developing reliable solid-state thermoelectric power generations that are quiet and efficient for front line deployment. We are pleased to be developing system concepts, fuels, materials and components for the reemergence of space nuclear power systems.

In the commercial energy arena, we are providing engineering services to utility companies, primarily to clear up their nuclear safety problems. We are developing safe gas-cooled power reactors and reactor fuels. We are conducting the most advanced fusion power experiments in the world today. We are building fail safe TRIGA research and small power reactors. We are also conducting advanced materials and processes research and development in support of the nuclear power industries.

GAS COOLING TECHNOLOGY – DERIVATIVE OF HTGR AND GCFR PROGRAMS



G-287(3)

The development of the High Temperature Gas-Cooled Reactors (HTGR) and Gas-Cooled Fast Reactors over the last 20 years have created a technology base at GA that is applicable to space power needs.

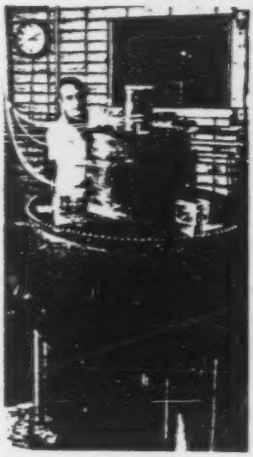
GA has developed entire power systems, from conception through manufacture and operation. The Fort St. Vrain 330 MW (e) HTGR, the TRIGA reactor system, and the operating Doublet III fusion device are outstanding examples of safe, efficient, and reliable nuclear power systems conceived, developed, manufactured, tested and operated by GA Technologies Inc.

GA's expertise in materials, components, and systems are available to the space power program.

AT THE FOREFRONT OF FUSION RESEARCH

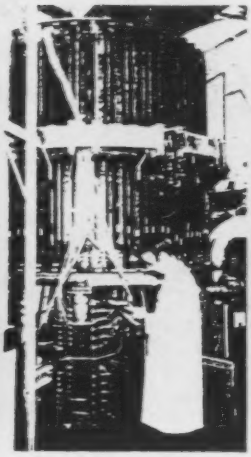
DOUBLET I

FORMATION OF FIRST NON-CIRCULAR PLASMA IN A TOKAMAK - 1969



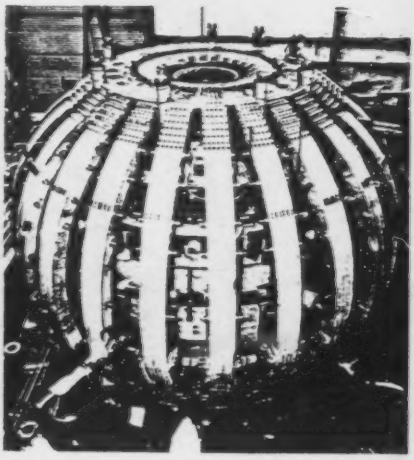
DOUBLET IIA

DEMONSTRATES ADVANTAGES OF DOUBLET PLASMA SHAPE - 1977



DOUBLET iii

LARGEST OPERATING FUSION EXPERIMENT–U.S./JAPAN COOPERATIVE PROGRAM



GA has been engaged in fusion research for the past 20 years. Development is directed toward compact fusion reactors for efficient, low-cost electrical power generation. Three experimental Tokamaks have progressed through demonstrations of plasma shaping and confinement and have passed to the ohmic heating phase achieving plasma temperature of 20 million degrees. The program has now entered the neutral beam heating phase which will increase temperatures toward reactor levels.

The GA Fusion Program is sponsored jointly by the U.S. Department of Energy and the Government of Japan.

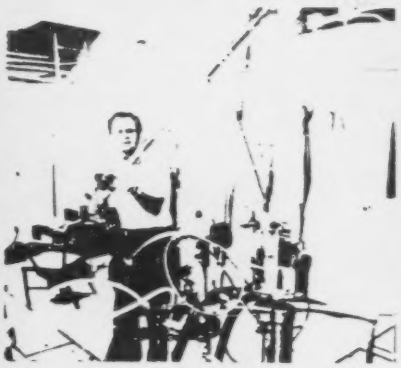
TRIGA REACTOR FACILITY

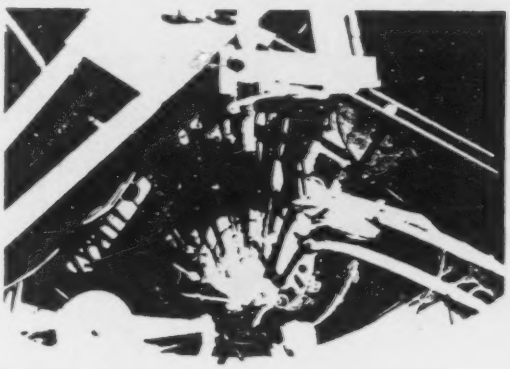
FUEL DEVELOPMENT

- NONDESTRUCTIVE FUEL ASSAYS
- FISSION GAS RELEASE STUDIES
- NEUTRON ACTIVATION

RESEARCH AND DEVELOPMENT CAPABILITIES

- ACTIVATION ANALYSIS · TRACE IMPURITIES
- NEUTRON RADIOGRAPHY SERVICES
- ISOTOPE · RESEARCH AND MEDICAL
- IRRADIATION TEST · STEADY-STATE OR TRANSIENT





During the 1950's decade, GA developed and demonstrated the first nuclear reactor designed for training, research, and custom production of radioisotopes. It was named TRIGA for **T**raining – **R**esearch – **I**sotopes – **GA**. This multi-purpose reactor was designed for training research scientists and has capabilities for research in chemistry, physics, metallurgy, biology and medicine.

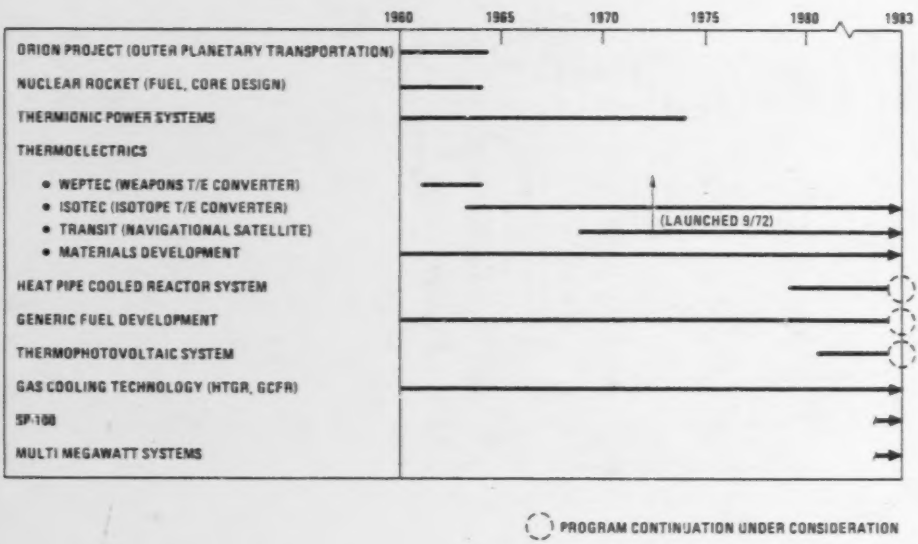
TRIGA uses a zirconium-hydride moderator blended with uranium to form a solid metal alloy fuel. Since they are alloyed, any sudden increase in power heats fuel and moderator simultaneously. The higher temperature instantly makes the moderator less effective and automatically returns the reactor to its normal operating level.

GA has builit 65 TRIGA reactors that are deployed worldwide. TRIGA's have recorded more than 650 reactor years of totally safe operation.

22-828 O—83——15

GA SPACE NUCLEAR POWER EXPERIENCE — EXTENSIVE

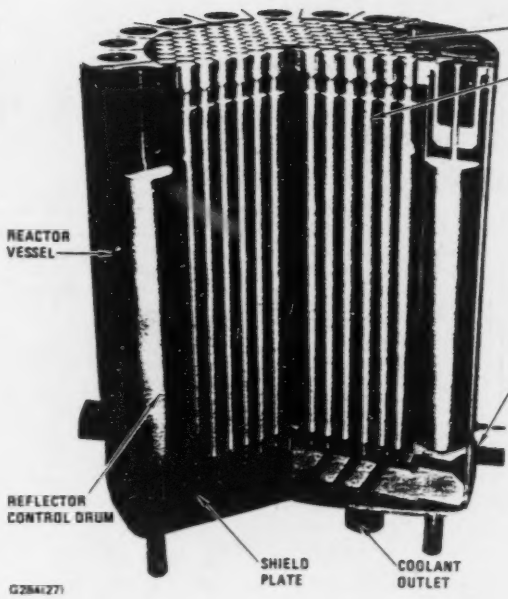
GA SPACE NUCLEAR POWER PROGRAMS CURRENT STATUS



G-297(8)

GA has been an active participant in space nuclear power programs since the 1950s. While most space nuclear power activities were terminated in the early 1970s, GA has maintained its expertise in thermionics and continued to develop space power technology in the areas of thermoelectric materials and systems, advanced nuclear fuels, gas-cooled reactor components and systems. GA is under contract to the Jet Propulsion Laboratory for space power conceptual studies in the 100 kilowatt class and is also developing systems concepts for growth to multi-megawatt electrical output.

IN-CORE THERMIONICS – A GA TECHNOLOGY

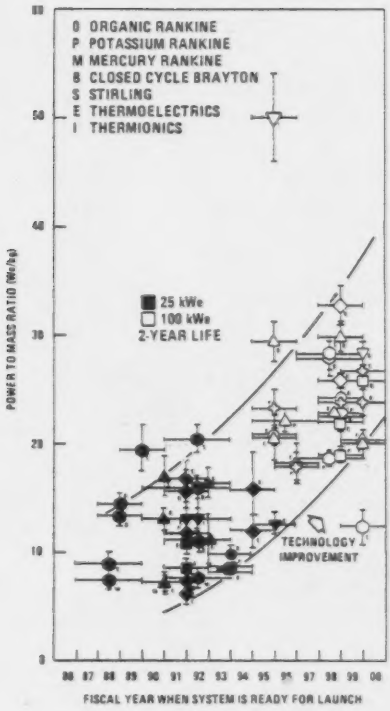


KEY FEATURES – DEMONSTRATED

- THERMIONIC FUEL ELEMENTS PRODUCE ELECTRIC POWER DENSITY IN REACTOR CORE
- REDUNDANT STATIC POWER CONVERSION
- LOW MASS/VOLUME (DUE TO SMALL RADIATOR)
- SCALABLE TO HIGH POWER (MULTI-MEGAWATT)

Thermionics technology was developed at GA between 1959 and 1973, and in 1969 GA was chosen by the AEC to develop in-core thermionic reactor systems. A thermionic fuel element manufacturing facility was established and lifetimes of 1.4 years in-pile and 5.3 years out-of-pile were demonstrated. The technology is attractive because system mass and volume are low, a consequence of the high heat rejection temperature. The technology is readily scalable with a minimum of additional engineering. System designs ranging from 100 kW (e) to several megawatts were developed. The overall program costs were about $20-million.

COMPARATIVE EVALUATION POWER TO MASS RATIO



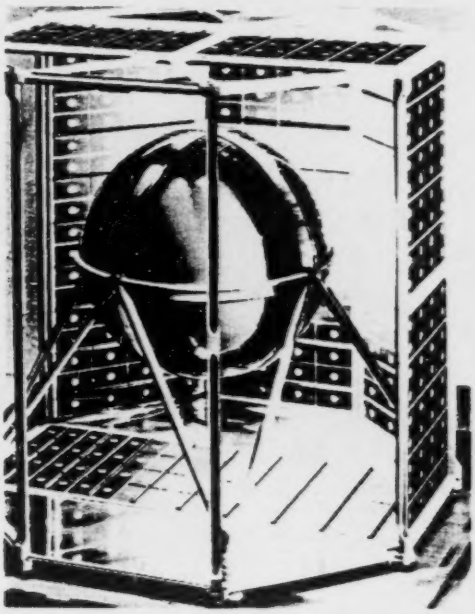
SOURCE: ROCKWELL INTERNATIONAL STUDY – "SPACE REACTOR ELECTRIC SYSTEMS" 29 MARCH 1983

G-299(7)

The low inherent mass and volume of in-core thermionics systems result from the in-core conversion of heat to electricity and the inherent high heat rejection temperature which yields a small radiator. Recent comparative evaluations by Rockwell International for DOE indicated the power-to-mass ratio for in-core thermionics systems is about a factor of two better than for other candidate space nuclear power systems. In view of the advanced state of thermionic power converter development, a much earlier launch date could be achieved.

THERMOELECTRIC MATERIALS AND SYSTEMS
TRANSIT NAVIGATIONAL SATELLITE

35 WATTS
LAUNCHED IN 1972
STILL OPERATIONAL

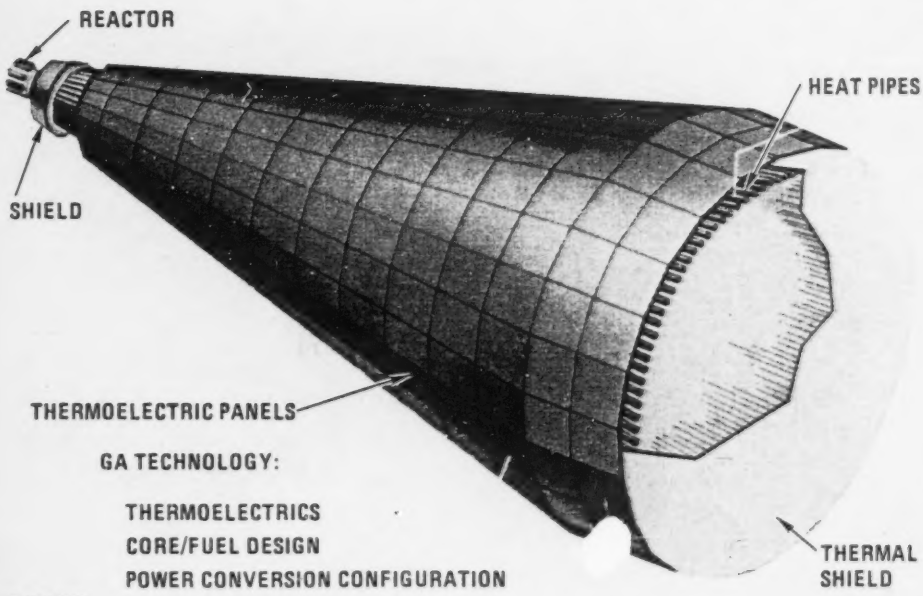


G-284(19)(R)

The 35 watt TRANSIT navigational satellite was designed, tested, and fabricated by GA Technologies for the Navy. The plutonium oxide (radioisotope) heat source was supplied by Mound Laboratories through the AEC. The thermoelectric materials were lead-telluride alloys, with the system designed to operate between 670 K and 410 K.

This space power system was launched in 1972 and still generates adequate mission power.

HEAT PIPE COOLED REACTOR SYSTEM



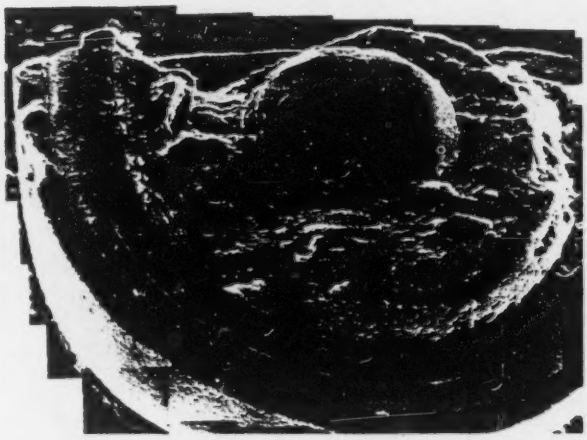
GA has been supporting the Los Alamos development of heat pipe-cooled reactor power systems for several years. The reactor is an assembly of small uranium bearing tiles in intimate contact with many heat pipes which remove fission heat from the core past the shield to the power conversion region. Electricity is produced by thermoelectric elements which receive radiant heat from the heat pipes. The cold side of the thermoelectric elements comprise the radiator. GA has made significant contributions in the following areas:

- Development of coated fuel particle compacts which, because of their good dimensional stability, are very compatible with heat pipes.
- Improved thermoelectric materials.
- The engineering design of the heat pipe – thermoelectric power conversion system.

HTGR FUEL = FUEL FOR SPACE POWER

COATED PARTICLES:

- APPLICABLE TO SEVERAL SPACE NUCLEAR POWER CONCEPTS
- PARTICLES SHOW NO SWELLING WITH BURNUP

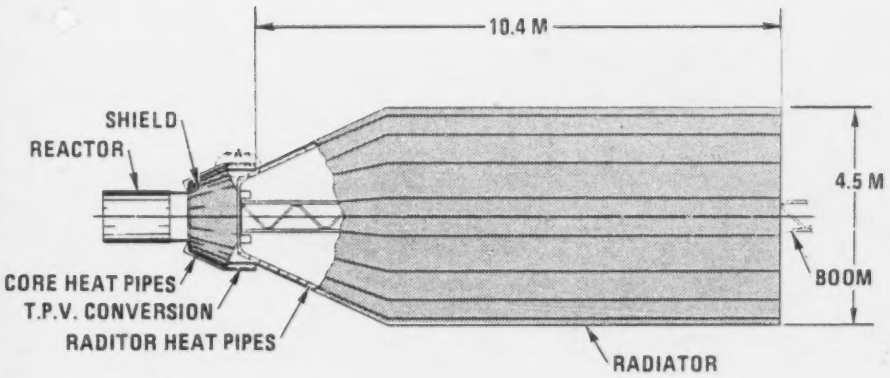


G-287(4)

The coated fuel particles developed for the high-temperature gas-cooled reactor (HTGR) program have a broad applicability to space power reactors because of their dimensional stability under irradiation. Thermionic reactors, heat pipe-cooled reactors and gas-cooled reactors have improved performance with coated fuel particles. This fuel was also the basis for NERVA and KIWI reactor cores.

Coated fuel particles development, manufacture, and operation continues at GA under the HTGR program.

THERMOPHOTOVOLTAIC SYSTEM



G-284(24)

Photovoltaic cells have been extensively used to provide power in space. However, solar photons are inefficiently absorbed by existing PV materials, yielding thermal-to-electrical efficiencies in the range of 10% to 15%. Photons from incadescent materials, such as tungsten, operating above 1500 K, can be absorbed more efficiently with conversion efficiencies as high as 30%. The energy for the emitter can come from concentrated solar energy, radioisotopes, or nuclear reactors. GA explored its use as a space power concept in 1980, and subsequently, developed a conceptual design for a space power system. Unfortunately, there were no government funds provided in 1983 for this important development.

ON-GOING SYSTEMS STUDIES

- 100 KW(e) SYSTEMS STUDY
  - SP-100 PROGRAM UNDER CONTRACT TO JPL
  - SELECT BASELINE, BACKUP AND GROWTH CONCEPTS
- MULTI-MEGAWATT CONCEPTUAL DESIGN STUDY

  PROPOSAL TO NASA-LEWIS

G-299(1)

GA has developed entire power systems, from invention through manufacture to operation. The Fort St. Vrain 330 MW (e) HTGR, the TRIGA reactor system and the operating Doublet III fusion device are current examples.

SPACE NUCLEAR POWER AN EMERGING NEED

SPACE NUCLEAR POWER
THE ENABLING TECHNOLOGY

- ABOVE ABOUT 20 KW(e), NUCLEAR POWER IS THE TECHNOLOGY OF CHOICE
  - SIZE
  - WEIGHT
  - COST
- SURVIVABILITY
- MANEUVERABILITY
- OPERABILITY
- DIRECTED ENERGY WEAPONS
- LEO-GEO TRANSPORT AND SPACE CLEANUP VEHICLE
- PLANATARY EXPLORATION
- SPACE STATIONS

G-284(7)(R)

Larger power sources are needed in space for the more obvious reasons given below, but also for many more subtle reasons:

- The need to miniaturize systems and components in the payload will be reduced.
- Space-earth communications can depend on larger, faster and more reliable transmission systems.
- Hardening of payload electronics will be facilitated.

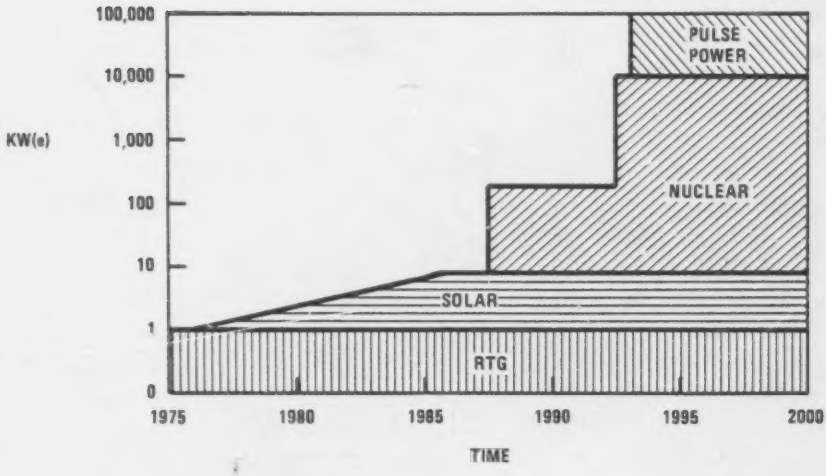
APPLICATIONS FOR SPACE NUCLEAR POWER SYSTEMS

POWER RANGE	1-25 kW(e)	25-500 kW(e)	MEGAWATTS
ENERGY SOURCE	SOLAR RADIOISOTOPE NUCLEAR	NUCLEAR POWER	NUCLEAR POWER
COMMUNICATIONS	X		
NAVIGATION	X	X	
WEATHER	X	X	
HARDENED C^3		X	
SPACE-BASED RADAR		X	
BLUE-GREEN LASER		X	
ELECTRONIC JAMMERS		X	
SPACE TELESCOPES		X	
ELECTRIC PROPULSION		X	X
LUNAR BASE/OPERATIONS			X
ORBITAL TRANSFER VEHICLE		X	X
DIRECTED ENERGY WEAPONS			X
SPACE STATION	X	X	X
PLANETARY EXPLORATION	X	X	X

G-287(10)

High power levels in orbit are necessary for foreseeable civilian missions as well as for military missions.

NEEDS VS. OPTIONS



G-284(7)

Nuclear power systems could be ready for space applications in the late 1980s at power levels in the range of 100 kW (e) and in the early 1990s for higher power levels. The technology of choice will depend on a clear definition of mission and the resulting requirements. In any event, it will be important to develop a technology that is scalable between 100 kW (e) and a megawatt with a minimum of additional engineering and R & D.

Pulsing power for defense purposes is also a 1990s technology.

CURRENT STATUS SPACE NUCLEAR POWER PROGRAM

U.S. PROGRAM NOW WELL COORDINATED

SP-100 PROGRAM

- DARPA, NASA, DOE JOINT EFFORT
- DARPA PROGRAM MANAGER
- JPL PROJECT MANAGER
- SYSTEMS STUDIES:
  - 100 KW(e): GA, W, GE UNDERCONTRACT TO JPL
- NATIONAL LABORATORIES INVOLVED AS RESOURCE CENTERS
- TECHNOLOGY PROGRAMS BEING DEFINED
- MULTI-MEGAWATT SYSTEM STUDY THROUGH NASA-LEWIS

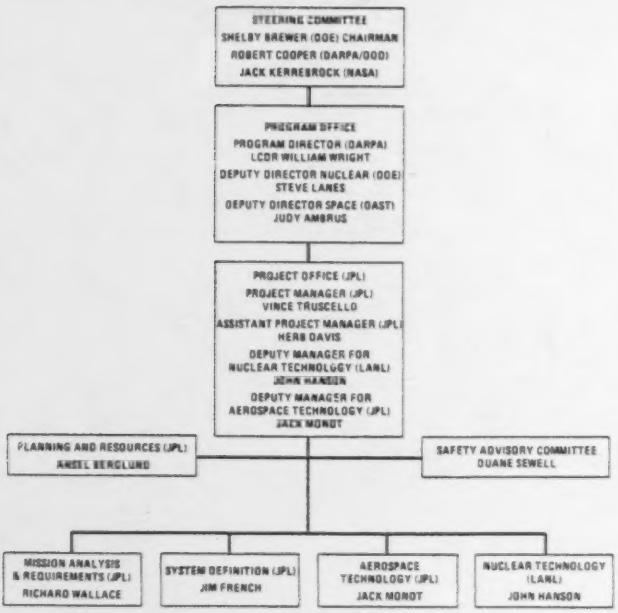
G-287(6)

The Memorandum of Agreement between DARPA (for DOD), NASA and DOE was signed on February 11, 1983, and assured the orderly initial development of nuclear power technologies for space.

The focus is technology development, initially for 100 kW (e) applications but also for multi-megawatt applications as appropriate.

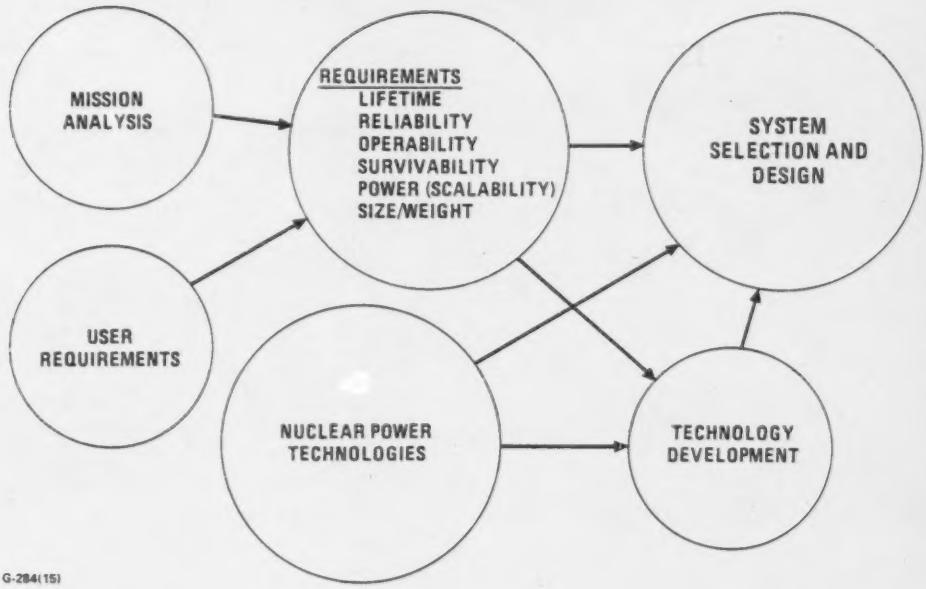
System studies and mission analysis are also key elements of the program to assure that technology development and mission requirements are at all times related.

SP-100 PROGRAM ORGANIZATION



G-287(7)

SYSTEMS EVALUATIONS
REQUIREMENTS WILL GOVERN CONCEPT SELECTION



Systems studies in progress begin with measuring candidate power system technologies against a set of assumed requirements. An evaluation of the shortcomings of the various technologies results in the selection of a power system for more detailed study and a related technology development plan.

On-going mission analyses and interaction with potential users will result in a modified set of requirements. This will in turn affect design studies and development plans. This iterative procedure will assure the timely development of an appropriate technology.

TECHNOLOGY BUILDING BLOCKS WILL PACE SYSTEMS DEVELOPMENT

TECHNOLOGY NEEDS	POWER CONVERSION TYPES					
	THERMIONIC	BRAYTON CYCLE		THERMO-ELECTRIC	RANKINE OR STIRLING/ CYCLE	THERMO-PHOTOVOLTAIC
		OPEN CYCLE	CLOSED CYCLE			
• IMPROVED NUCLEAR FUEL	√	√	√	√	√	√
• IMPROVED MATERIALS						
STRUCTURAL MATERIALS	√	√	√	√	√	√
INSULATORS	√			√		√
REFRACTORY METALS	√	√	√	√	√	√
THERMOELECTRICS				√		
• HEAT PIPES			√	√	√	√
• RADIATORS	√		√	√	√	√

G-284(16)

The current state of knowledge on missions and requirements indicates a need for technology development in certain key areas: improved high temperature structural and other materials, longer-life nuclear fuel materials, lighter and more volume-efficient radiator and improved heat pipes. The payoff is reduced in-orbit mass and volume, and more reliable systems. Work in these generic technologies is a high-priority activity and should be funded accordingly.

REACTOR SPECIFIC TECHNOLOGY NEEDS

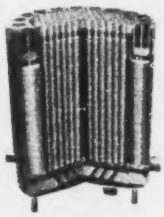
	THERMIONICS REACTOR	GAS COOLED REACTOR		HEAT PIPE COOLED REACTOR	LIQUID METAL COOLED REACTOR
		PARTICLE BED CORE	FUEL PIN CORE		
LONG LIFE FUEL PINS			√		√
HEAT PIPE R&D				√	
METAL FRITS (PARTICLE CONTAINERS)		√			
GENERIC COATED PARTICLE FUEL	√	√		√	

G-287(11)

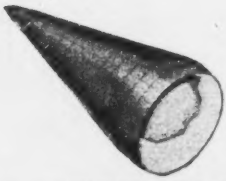
Reactor specific technology development efforts are necessary to assure that system design and development can proceed in a timely manner once final technology decisions have been made. Of major importance is the development of dimensionally stable long-life fuel elements. Heat pipe R & D and metallic frit development (for open cycle gas-cooled reactors) are also long-term needs.

ALTERNATIVE SPACE NUCLEAR POWER SYSTEMS — A ROADMAP

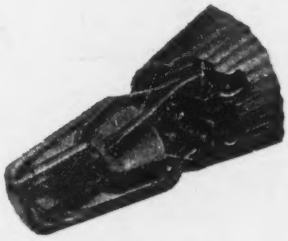
POWER CONVERSION OPTIONS



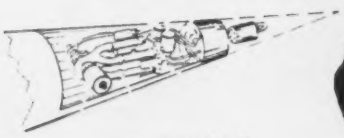
• IN-CORE THERMIONICS



• HEAT PIPE REACTOR/ THERMOELECTRIC

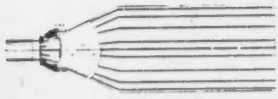


• BRAYTON



• RANKINE

•STIRLING



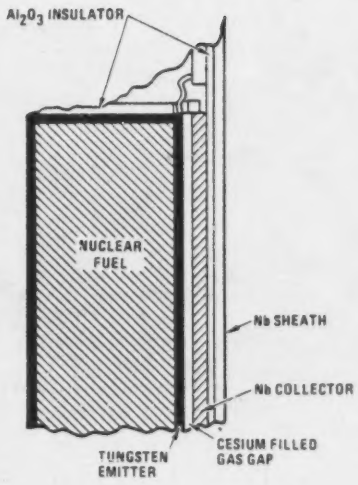
• THERMOPHOTOVOLTAIC

G-284(1)

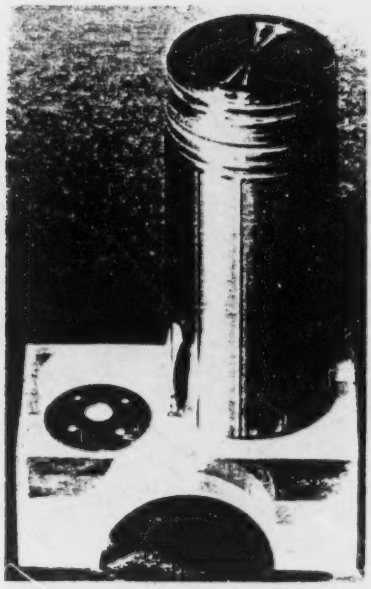
Power system alternatives can be characterized by the power conversion subsystem. Six conversion alternatives appear potentially attractive for space power applications.

- Thermionic
- Brayton Cycle — Closed and Open
- Thermoelectric
- Thermophotovoltaic
- Rankine Cycle
- Stirling Cycle

THERMIONIC CELL

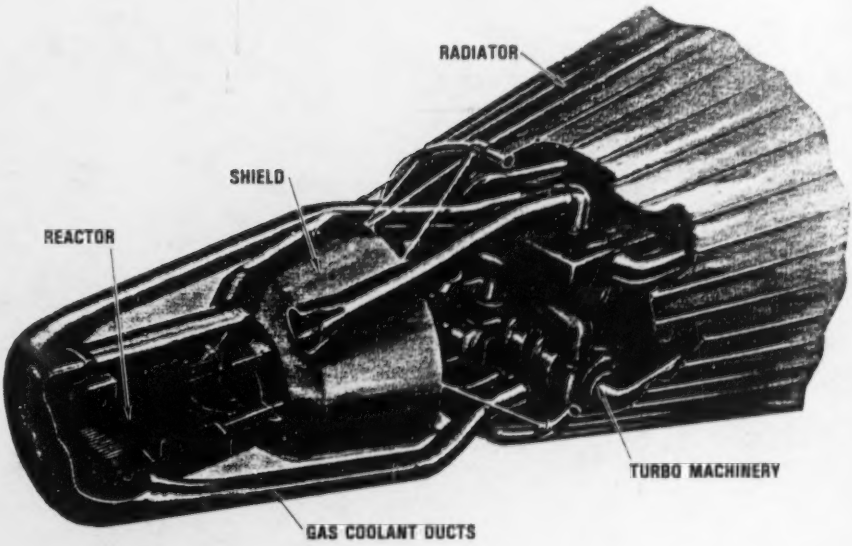


G284(23)



Thermionic systems contain many small series-connected thermionic cells. Thermionic cells are composed of nuclear fuel encased in a hot emitter, usually tungsten, and a neobium collector, the two being separated by a cesium (gas) filled gap. The cesium reduces the space charge effect as electrons boil off the emitter and fall into the reflector. Suitably designed electrically, a highly reliable (redundant) system results. Fuel cell lifetimes (in-core) of up to two years have been demonstrated. These systems are scalable to high megawatt outputs by adding more cells and degrade gracefully as individual cells degrade. Thermionic systems are efficient and yield highest power to mass ratios.

NUCLEAR BRAYTON CYCLE SYSTEM



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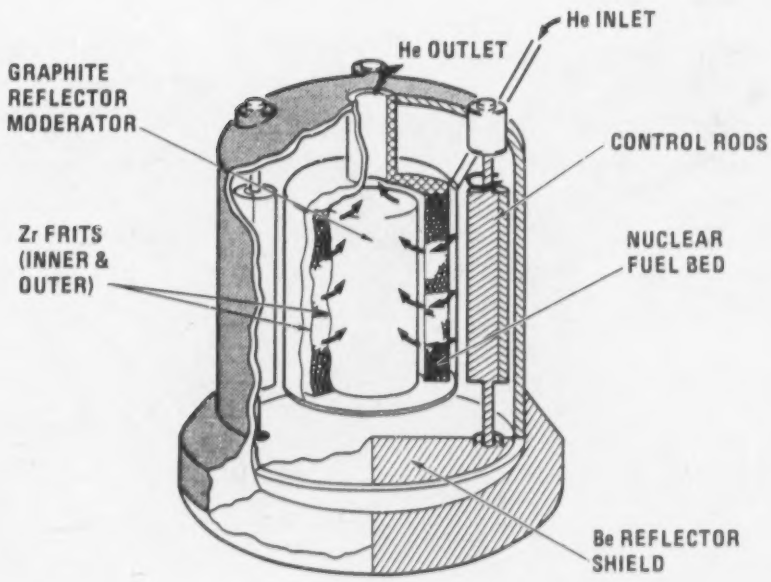
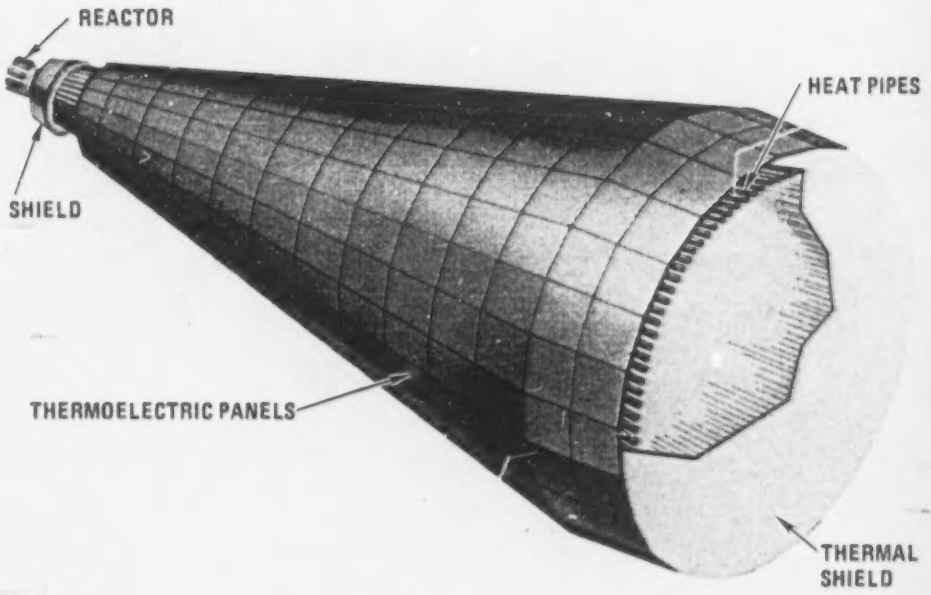
The Brayton cycle involves expanding a noble gas, typically a mixture of helium and argon, through a turbine-generator system. Existing materials and technology could be used to design a 100 kW (e) system, although it would be relatively heavy and bulky. Higher power systems would require advanced, high-temperature materials. The heat source could be one of several reactor technologies.

OPEN BRAYTON CYCLE (FIXED BED REACTOR) SYSTEM



The open Brayton cycle, using particle bed reactor technology developed by Brookhaven National Laboratory, appears capable of multi-megawatts of steady-state power hundred of megawatts for short time periods. The fuel over which the gas flows was developed by GA for operational high-temperature gas-cooled reactors. Since heat transfer from the fuel to the coolant is very good, the maximum fuel temperature and outlet gas temperature are similar, resulting in high efficiency.

HEAT PIPE COOLED REACTOR SYSTEM



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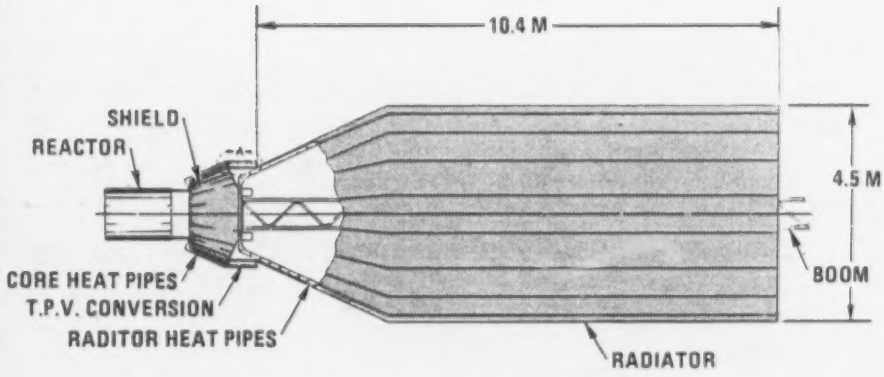
A current example of the use of thermoelectric power conversion system involves the heat pipe-cooled reactor developed by Los Alamos National Laboratory. The compelling feature of thermoelectric is system reliability. However, efficiency tends to be low, typically less than 10%. Thermoelectric power conversion has been extensively used in the past in space with radioisotopes supplying the heat.

THERMOPHOTOVOLTAIC SYSTEM



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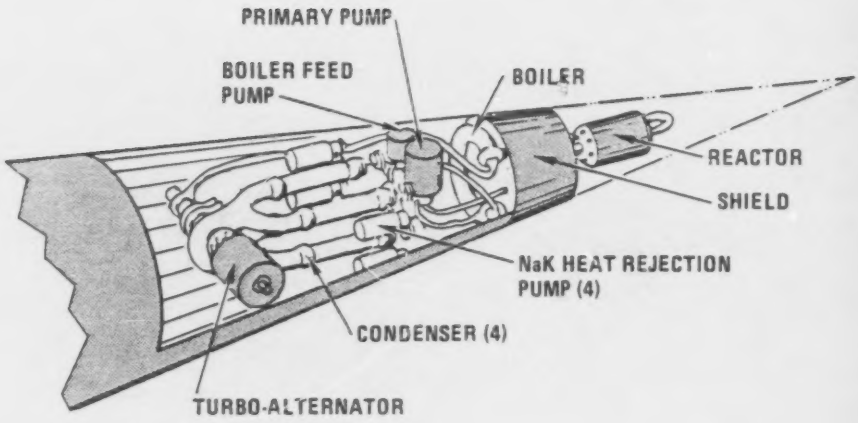
Thermophotovoltaic power conversion relies on matching the energy of photons emitted by incadescent emitters to the properties of photovoltaic materials. A properly designed system can yield efficiencies in the range of 20% to 30% and result in smaller and lighter space power systems. This efficient power conversion technology is an attractive option for the 1990s and should be funded for development now.

NUCLEAR RANKINE CYCLE SYSTEM



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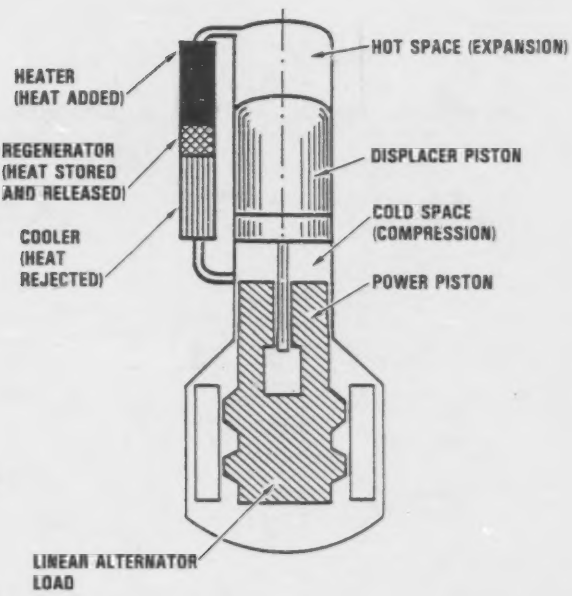
A Rankine cycle involves formation of a vapor inside the heat source, expansion of the vapor through a turbine power converter, and condensation of the cooling vapor prior to recycling through the heat source. Although this type system would be somewhat heavy and bulky, a 100 kW (e) system can be developed from off-the-shelf materials and technologies. Higher power Rankine systems depend upon development of advanced high-temperature materials because materials corrosion could degrade system life and stability of the criticla liquid-vapor interface.

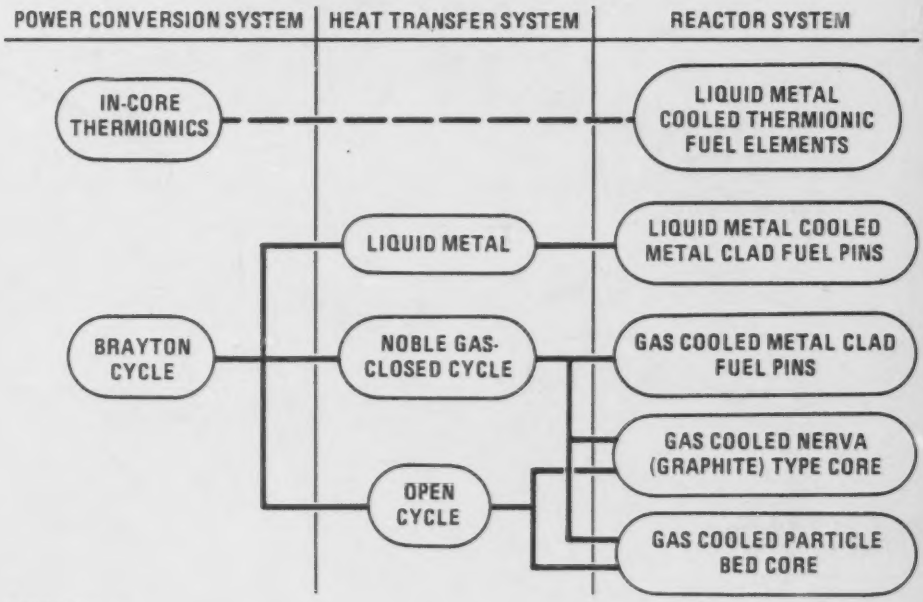
FREE-PISTON STIRLING CYCLE SYSTEM



SOURCE: MTI MECHANICAL TECHNOLOGY INCORPORATED

The Stirling system represents another option for power conversion. Its major advantage is high efficiency. A limited development program is under way.

ROAD MAP TO ALTERNATIVE SPACE NUCLEAR POWER SYSTEMS



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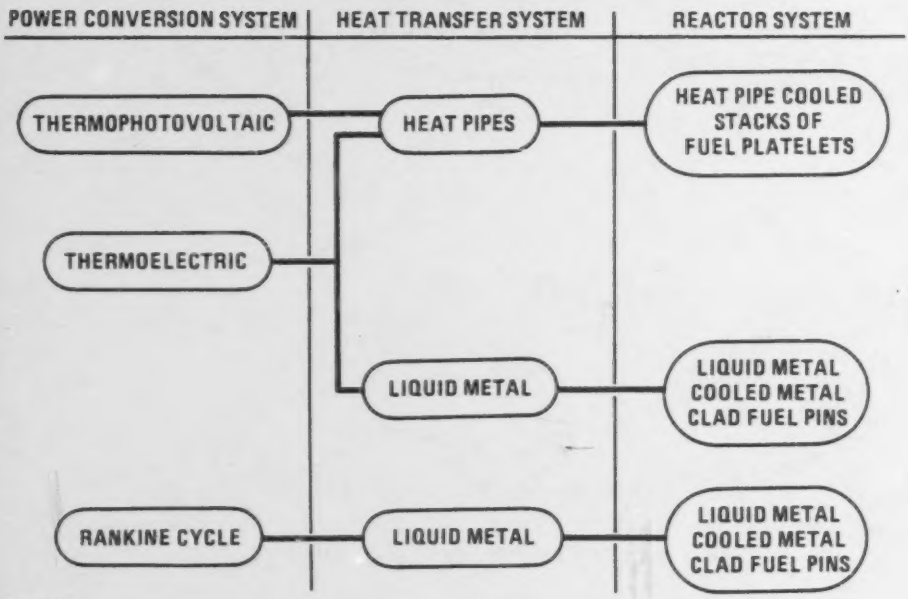
ROAD MAP TO ALTERNATIVE SPACE NUCLEAR POWER SYSTEMS



While there are a large number of nuclear power systems that could be created by different combinations of power conversion and reactor subsystems, only a few merit development consideration. GA Technologies has expertise in all of the efficient systems. The systems of choice will evolve from mission analysis and resulting requirements.

SUMMARY

- **GA – Space Nuclear Power Expertise**

  Advanced Nuclear Fuels
  Advanced Reactors
  Advanced Power Conversion

- **Nuclear Power – Space Enabling Technology**

  Civil Space Science & Exploration
  Ballistic Missile Defense
  Space Systems Positioning & Self-Protection

- **Available Technology Options**

  Requirements Drives Choices
  Technology Available for Systems Now
  Scalability for Growth

- **Space Nuclear Power Program**

  SP-100 Organized & Underway
  Technology Development Must Continue
  Funding is Inadequate

Mrs. LLOYD. Thank you, Dr. Dahlberg. Thank all of you gentlemen for being with us and being so responsive.

Mr. Anderson, I understand that you're responsible for coordinating the recent DOE evaluation study. Would you give us a little bit of information about the study?

Mr. ANDERSON. Certainly, Madam Chairman.

There were actually two studies that Rockwell performed. The first, which was contracted in September 1982 by the Department of Energy, was an evaluation of the various building blocks or subsystems that are used in putting together a reactor system. We did this study to bring to the forefront what was done in the past and show how it might be used in the future. Recently, we were requested by the SP-100 program to present a 3-hour briefing on that study to contractors, industrial participants, national laboratories and users at the JPL. We did that, and I believe it was a worthwhile effort in order to let everyone know where technology was and where it can go.

We also were the system integrator for a series of system studies--preliminary studies—that were done earlier this calendar year. In that study we integrated—into systems—reactors that were designed by national laboratories and industrial contractors. This was done in order to give an overview to the DOE and others as to what the capabilities of those reactors might be in a system.

Mrs. LLOYD. Thank you.

There are a lot of questions as to the present status of our technology base should some near-term space mission be needed. What technology base do we have that could be brought to bear if a near-term mission should be on the horizon? Would we have to rely on old technology. Just where are we on our technology base at the present time? We know we're building on past experience, but where does this really leave us.

Would anyone like to comment?

Dr. ARNOLD. If I may. There are several aspects of a reactor development program, some of which are perishable in time and some of which are not, some which can be taken from other programs. For example, the ability to design and to analyze reactor behavior is more a function of computer capability and the ability to use nuclear codes which has advanced considerably as time has gone on and comes basically from the continuation of the civilian reactor programs. In that sense that technology, with again some adaptation to the particular reactor that met the mission requirements, has advanced through the years.

As I mentioned earlier, the infrastructure would have to be pulled back together but that's not a matter so much of technology status as it is a matter of getting the necessary people, funding, and facilities in place. I think one area where we would probably wish that technology had been pursued continually, in the years since the NERVA and SNAP programs were pinched off, is that of materials development. I would agree with Dr. Harms in that area.

Mrs. LLOYD. I was wondering whether you would make the point that Dr. Harms made.

Dr. ARNOLD. There are some things that we could have been doing in those years that would help us with a higher performance system, but we could fly something on an earlier schedule, with

less performance, or we could do some more materials development and get higher performance systems.

Mrs. LLOYD. Dr. Dahlberg?

Dr. DAHLBERG. It's our view that you could fly a system of several tens of kilowatts in this decade. You would use a technology that is now available; it would be a relatively low temperature technology. The result would be a system which is relatively heavy and large in volume but it would work and it would work well. The advantage of a higher temperature technology for future higher power systems is to keep the volume and the weight down to meet mission requirements.

Mrs. LLOYD. Is volume a critical factor over weight?

Dr. DAHLBERG. It depends on what the mission is and I don't know the answer to the question. Both volume and weight appear to be very important, which is more important I don't know.

Mrs. LLOYD. How is our technology base compared with the Soviet's?

Mr. ANDERSON. I think the most interesting thing to know is that one version of the Soviet reactor, the Rumashka, is actually the SNAP-10—not the SNAP-10A. SNAP-10 was designed by Atomics International in the very early fifties but AI decided to pursue a more advanced technology—SNAP-10A. If you look at drawings of the SNAP-10 and the Rumashka you will find them very similar. That Soviet reactor technology plus other Soviet reactor technologies, I would say, are not as advanced as what the United States is talking about pursuing today the SP-100 program is talking about pursuing. So there is quite a difference between what they are doing and what we are talking about doing. What the Soviets are doing may be more equivalent to pre-SNAP, but their systems have higher powers than SNAP-10A, so the Soviets have more power capability in space, although not as much performance.

Mr. ROSENBERG. There are several other differences. The Soviet missions are primarily ocean surveillance at relatively low altitudes.

Mrs. LLOYD. What are their mission objectives?

Mr. ROSENBERG. I assume to view shipping and other ocean-going vessels. As a result they are operating at about 150 nautical miles. At 150 nautical miles solar panels have so much drag that the Soviets are in a position where they must use a nuclear power source in order to eliminate that drag.

The missions for which we are about developing requirements are in a higher power regime and presumably at higher altitudes. For example, a space based radar system which is one of the potential applications would require high power. I believe if we're talking about future mission requirements and future power requirements, our needs are radically different from what the Soviet's have already done and I believe it's a relatively low technology that they've used.

Dr. WOLFE. Could I just add a comment. I agree with everything the panel has said, except I would make the observation that to put up a Soviet-type satellite reactor, just to duplicate them, would also take us 7 years, in my opinion. I think that we have the technology available to jump over their present reactor systems. I think this is the consensus of everyone who talked here today. Nevertheless, we

ought to understand that you have to get started to do it or we will be here in 10 years wondering how we are going to leapfrog their next generation.

Mrs. LLOYD. Let's talk about money then. Do you think that we are putting sufficient funding into the SP-100 program to develop these capabilities?

Mr. ROSENBERG. I think for what we're trying to do in the first phase of the program that it is adequate funding. The decision is going to have to be made, in approximately 1985, as to what the next steps are and how much funding will be required at that time. But for the present there is adequate funding.

Dr. ARNOLD. If the question is just, is there funding in the SP-100 program to make a decision on the reactor type; the answer is yes. There's nothing there to do serious development of the reactor itself.

Mrs. LLOYD. But it really has sufficient funding to develop the prototype?

Dr. ARNOLD. Well, that's not part of the program funding we're talking about.

Mrs. LLOYD. How are your space reactor programs funded?

Dr. ARNOLD. We're about half on company funding and about half on DOE funding at the present time.

Mrs. LLOYD. What sort of investments have your firms made? Dr. Dahlberg, would you like to reply to that?

Dr. DAHLBERG. Well, the ratio of private to outside funding is about the same for GA as for Westinghouse. Over the years GA has spent about $100 million in current dollars on space power programs, and several hundred million on technologies applicable to space nuclear power.

Dr. ARNOLD. The Westinghouse figures over the 25 years would be escalated to today's dollars about $1 billion from the U.S. Government and about $50 million of our own.

Mrs. LLOYD. Mr. Anderson?

Mr. ANDERSON. We're about the same. We're currently funded by the SP-100 program, and had the prior DOE funding. We're funding about 50-50 in this area.

Mrs. LLOYD. Is there any foreign interest in our space reactor technology products? I mean from foreign countries is there any interest in our technology?

Mr. ROSENBERG. I have not heard of any.

Dr. ARNOLD. I have no information on that.

Mrs. LLOYD. What is GE spending in their program?

Mr. ROSENBERG. First with respect to the current SP-100 effort: General Electric is utilizing its own resources at a level equivalent to its present contract for the analysis and conceptual design of a space-based nuclear power source. These resources coupled with Government funding directly relate to improving technology base required for a successful program.

Second and of significant importance is the technology base, which is our starting point, and which has been developed over the years by Government funding and by our own research. I refer only to that portion that directly relates to the space-based nuclear power source and I reference these in terms of today dollars for ease of comparison.

In the nuclear technology area, such technologies as fuel development, heat transport, liquid metal components and systems, shielding, safety and space configurations, the Government has expended over $2 billion. In addition, General Electric has added to that data base by its own internally funded research and development amounting to another $50 million. A large portion of this has been in the specific area of fuels development.

In the area of energy conversion, the Government has funded General Electric over 250 million equivalent dollars for thermoelectrics and $250 million in dynamic systems and heat exchangers. We have spent the equivalent of $30 million of our discretionary funds in support of related energy conversion technologies.

In summary, a data base amounting to more than $2.5 billion exists at General Electric just in Government funding and it approaches $2.6 billion when our own research funds are included.

Mrs. LLOYD. Of course, there's tremendous interface here as well.

Mr. ROSENBERG. Oh, yes.

Mrs. LLOYD. Mr. Lujan?

Mr. LUJAN. Thank you, Madam Chairman.

I guess by foreign interest, has anybody put up any money? That's how they would show any interest.

Mr. ROSENBERG. We have had none.

Mr. LUJAN. Do you all have contracts with either NASA, DOE, or DARPA?

Mr. ROSENBERG. We have both DARPA and DOE contracts.

Mr. LUJAN. You talk about hundreds of millions, and, in a couple of cases, of billions. What I see is $12 million total funding for those three agencies. You're talking in terms of the SNAP programs?

Dr. ARNOLD. SNAP's and NERVA's over the past 25 years; yes.

Mr. LUJAN. Are you the only four companies that are participating in the SP-100 directly with DOE?

Dr. DAHLBERG. I think so, yes.

Mr. ROSENBERG. Some companies have partners or associates.

Dr. ARNOLD. We have a teaming arrangement with the Lockheed Co. who is our subcontractor on this.

Mr. LUJAN. I understand that but you get the funding and then you pay out.

Dr. ARNOLD. Yes, through JPL.

Mr. LUJAN. What amounts are we talking about for the four companies? How much outside contracting are they doing other than their laboratories?

Dr. ARNOLD. This is a half million each for the phase we're in. Two and a half million out of the 12 is going out to——

Mr. ROSENBERG. There are four contractors, so the total is $2 million. Half a million each.

Mr. LUJAN. Those four companies, were those the only four involved in the early 1960's in the development of a space nuclear reactor?

Mr. ANDERSON. Aerojet was involved. TRW was involved on SNAP-2. Vought Corp. was involved at that time and a few others.

Dr. ARNOLD. If I may add, for the reactor contract itself I think it's the four here. Aerojet, for example, was a partner with us on

the NERVA program for the engine part of the NERVA rocket engine. We were the reactor contractor.

Mr. LUJAN. What I'm trying to get at is the participation of the private system as opposed to what our own laboratories are doing. It appears to be like about a third of the effort now. Perhaps in the SNAP programs the same percentage because, after all, you're the ones who are going to build it in the final analysis. Isn't that correct, after all the research is done?

Dr. ARNOLD. Yes. I think the characterization of such a program is that in the early stages it will tend to be heavier in the national laboratories and in the later stages there will be considerable amounts of testing and component production, procurement, and eventually flight programs, so the funding will shift over to be predominately to industry with the national laboratories still in a monitoring and technical backup role.

Mr. LUJAN. Only one of the SNAP programs flew; is that correct?

Mr. ANDERSON. Yes.

Mr. LUJAN. Were other reactors produced and just tested on Earth?

Mr. ANDERSON. Well, there was the SNAP-2 reactor. There were two of those produced and tested on Earth in the 1950's and early 1960's. There were also the SNAP-8 reactors, which were about 500 kilowatts thermal. Two of those were tested for about a year in the 1960's, but they were never coupled to the subsystems that would have produced electricity. Those power conversion subsystems were tested separately. So a total system test was not done. It was planned but not done.

Mr. LUJAN. Not even 10A?

Mr. ANDERSON. SNAP-10A had a total system test and also a flight test.

Mr. LUJAN. Do you anticipate that SP-100 is going to be the same kind of technology involved?

Mr. ANDERSON. The SP-100 program currently has certain requirements on performance and you could never meet those with a SNAP-10A type technology. There would have to be improvements in temperature in order to meet the performance requirements of SP-100.

Mr. LUJAN. You're talking about fuels and materials?

Mr. ANDERSON. Fuels, materials, and shielding technologies to operate at the higher temperatures. The shields that we used in SNAP-10A used material that melts at 1,266 degrees Fahrenheit. As you go to higher and higher temperatures for the reactors, you may have to develop cooling methods for the shields. Things like this will have to be done.

Mr. LUJAN. How confident do you feel that SP-100 will be successful?

Mr. ANDERSON. In developing a technology roadmap, I feel quite confident.

Dr. ARNOLD. I think we should make it clear there is not currently a reactor development program. It is a program to lead to a selection of concept and then to go into a program.

Mr. LUJAN. Once you get to that.

Dr. ARNOLD. I think we are capable of choosing a reactor concept and type which is in turn capable of being developed successfully.

Mr. ROSENBERG. I would echo that. I'm completely confident that we will be able to develop the materials that are necessary as well as the proper safety precautions to make it a successful program.

Mr. LUJAN. I assume everybody does.

How long and how much?

Mr. ANDERSON. I think the total timespan before we get to a successful launch of a system is approximately a decade. Depending on the type of program that's undertaken and what the specification is, I think it would be premature to estimate what it would cost. That's going to depend to a large extent on what the mission requirements are, what the specifications are, and so on.

Dr. DAHLBERG. I feel more optimistic. It could take 10 years, but it doesn't have to take 10 years.

I might also point out that the current program is funded in the range of $10 to $15 million a year. In my view you're not going to make much progress on the technologies discussed here today on $10 to $15 million a year.

Mr. LUJAN. At the $12 million a year that we have now for developing the concept and finally coming up with one, is that sufficient for determination of which concept we will come up with? We can make that decision with $12 million a year? I assume that each one of you is ready to make a decision.

Mr. ANDERSON. I think that we can make that decision. In my testimony I stated I thought the funding was sufficient to come up with what we call the technology roadmap. I do not know if the funding is sufficient to perform any type of generic technology development.

Mr. LUJAN. I understand that. We're not at that point.

Mr. ANDERSON. Well, as I heard other people mention, specific activities like refractory material development, shield development, and fuel development, might be able to go on in parallel with the decision process. I do not know if the funding in the program is sufficient to do that in parallel with the technology roadmap activity.

Mr. LUJAN. Well, at the pace we're going is DOE, NASA, and DARPA, ready to or will they be ready in 1 year—have they specified a length of time to determine what kind of a reactor they want, what kind of a system they want—will they be able to do that in 1 year, 2 years?

Dr. WOLFE. I think we all believe that in 1985 there will be sufficient information to choose a path that would be successful. I personally believe, as my testimony indicated, that you could make a decision earlier.

Mr. LUJAN. Suppose you do that in 1985. A reactor is a reactor is a reactor. Are we talking about $500 million, $50 billion? I've given you wide enough ranges.

Dr. DAHLBERG. I think the mission requirements are going to determine the system of choice. Until the requirements are firm it's hard to decide which is the best system. Nevertheless reactor or system development in the past has typically cost $1 to $2 billion. I think that the funding for the space power program is going to have to escalate within 2 to 4 years to the range of $100 to $200

million a year if we're going to have something flying in the early nineties.

Mr. LUJAN. So you saying we're looking at $1 billion, $2 billion, $3 billion?

Dr. ARNOLD. I would agree with that.

Dr. WOLFE. I think one of the dangers of this kind of a program is that we take so much time to determine the right mission and the optimum system of that mission, which is, frankly, going to change with time, that we don't roll up our shirt sleeves and start to build an adequate system that would be useful for a number of missions of the type that Mr. Rosenberg mentioned. I think we can spend a lot of time debating. You hear some of the debates here but I think, in fact, that there are technical concepts to follow which will provide credible tens to hundreds of kilowatt reactors without—other than the materials I mentioned—a lot of extrapolation of technology.

Mr. LUJAN. You're probably right. At least what I gather from testimony and discussions, that for a space station we're going to be looking at 500 kilowatts or somewhere in that area to get started. Why don't we build a 500 kilowatt one and then if the military wants a 50 megawatt one, well, then, that's another problem that we go to. Why do we have to wait for the 50 megawatt one before even approaching the 500 kilowatt one? That's basically what you're saying and I think you're correct.

Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Lujan.

Mr. Volkmer?

Mr. VOLKMER. Thank you, Madam Chairman. I have a couple of questions.

Are facilities available to test space nuclear reactors in the 100 kilowatt class?

Dr. WOLFE. I think we have facilities at national laboratories that would allow us to test a number of the components, the fuel, and materials at prototypic temperatures, so, yes, there are facilities to do that. To put a whole ground-based system together, of course, you take a site and you need to put there the supporting facilities and then the investment then of building the ground-base system. I think in terms of component development there are facilities and equipment available. We would have to build some more perhaps for refractory metal development—bigger and better furnaces and such—but in general I don't see any major impediments there.

Dr. ARNOLD. I think as far as integrated test programs there are remnants of facilities left from the earlier programs which could either be refurbished or modified or could be duplicated. It's a matter of choice.

Mr. VOLKMER. Like Plum Brook?

Dr. ARNOLD. Plum Brook is one. I'm familiar with the facilities at the Nevada test site which would also be candidates, but there are other candidates.

Mr. VOLKMER. These would have to be refurbished to some extent though, wouldn't they?

Dr. ARNOLD. Yes; and some of them are being used for other purposes and then you have a conflict in whether you want to use them for this purpose or build a duplicate.

Mr. VOLKMER. Well, this is an area which we should be looking to.

Dr. ARNOLD. Yes, sir. As I said in my testimony, this is one of the critical program issues: What are the ground test facility plans for the ultimate program?

Mr. VOLKMER. All right.

Now, what do you see as the critical technical hurdle in the development of a space nuclear reactor?

Dr. DAHLBERG. The critical technologies are in the materials area: Fuels that don't change dimension under radiation, and high temperature metals that can be used for structural materials in both the reactor and the power conversion system.

Mr. VOLKMER. Would we need further research into those areas?

Dr. DAHLBERG. In the case high temperature metals, I believe we need to reestablish the industry which can supply the kinds of materials which are needed and we need to begin the test program which will prove out those materials. For fuels, I think it's a matter of reorienting programs which are already in progress toward this somewhat new application.

Mr. VOLKMER. As far as the metals part, we're going to have to look at that right away then?

Dr. DAHLBERG. In my view, you're right.

Mr. VOLKMER. Madam Chairman, we don't have any funds in 1984 for that; do we?

Mrs. LLOYD. In 1983 and 1984 we have funding for advanced nuclear power systems.

Mr. VOLKMER. All right. Some of that, in your opinion, should go to developing materials processes?

Dr. DAHLBERG. High temperature metals and long-life fuels.

Mr. VOLKMER. All right.

Now, based on extrapolation of known technology, do you see any problems in making a 100-kilowatt class reactor compatible with the weight and safety requirements?

Dr. DAHLBERG. I don't.

Dr. WOLFE. I think we all have conceptual designs that tend to meet those requirements. I would agree with what Dr. Dahlberg said on the R&D, that we certainly could start now, and will ultimately have to start, on high temperature metals development. The type of development work you do on the fuel depends directly on the results of the reactor design when you choose the design. If you're going to choose a gas-cooled reactor design, of the type that Dr. Dahlberg talked about, you have one situation. If you would choose a liquid-metal-cooled reactor, of the type I talked about, you would have a different situation. In particular, in our case, we think the liquid-metal-cooled fuel design would carry over directly from the existing technology base and that the major problem would be, as I said, the materials, the clad, and the structural materials, and not the UO2 itself, which we think we could use based on present technology in the LMFBR program.

Mr. VOLKMER. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Volkmer.

Mr. MacKay?

Mr. MACKAY. Thank you, Madam Chairman.

I'm not a high technology person. I even have trouble keeping track of writing notes and watching charts at the same time, so I can't remember whose chart it was. It seems to me I saw that there are other technologies that might be competitive with space nuclear electric power, and what are they or are they there or are there mixtures of technologies that should be explored.

Dr. ARNOLD. I could try that one. Page 7 of our expanded testimony is a chart trying to relate various technologies to each other, in which we look at two parameters, one is the power level you require—how many kilowatts or megawatts. The other is the duration. For short versus long duration at a given power you get a number of different answers and also you get different answers for at the same duration for different power levels. In that chart we try to compare chemical power sources, solar radioisotopes, and nuclear reactors. The general trend is such that for higher power levels and longer durations you're going to need a nuclear reactor.

For short durations you can use chemical. For low powers you can use chemical, solar, or radioisotopes. It's a combination of those two parameters. It's oversimplified, but it's an attempt to answer your question.

Mr. ROSENBERG. Mr. MacKay, you may have been referring to this chart which I showed during my testimony (chart 2). It is an attempt to show the limits of available power plotted against missions. Is this the one you were referring to?

Mr. MACKAY. Yes.

Mr. ROSENBERG. The two bands are the missions. In the lower left-hand corner, the chart begins with early communications satellite; goes on to defense communication satellites; and continues to planetary exploration and space station. Power requirements are shown on the left. The nuclear istope systems which have been used on many of the planetary probes to date have a limit of about 1 kilowatt, and they have other limitations as well. Fuel cells, which have to be generally refueled and have limited life can reach as high as 10 to 15 kilowatts, and solar arrays are approximately 25 kilowatts before they become impractical from a size point of view. If we compare that with the mission requirements, you can see that an advanced warning system would reach the approximate limit of the solar array, while at the same time the solar array is more vulnerable and less maneuverable than a space reactor would be. Thus, advanced warning systems tend to be on the borderline of reactor requirements. Laser communication with submarines require power which would go beyond the solar array capability. Not shown on this chart is space band radar which would also require higher power levels than can be practically achieved from solar arrays. Of course, higher power levels are shown for enhancement of planetary exploration, and for a space station, if we are considering ultimately processing metals and utilizing factory capability in space. Under these conditions, it is obvious we would need to go to a reactor power system.

Mr. MACKAY. The problem with this is when you say we need mission definition?

What if we were to say all of the above. It seems to me to be a very reasonable point.

Mr. ROSENBERG. I would agree with you. I tried to demonstrate two points with this chart. One, the missions themselves are time phased. If we're considering a power capability provided through reactors in the 1990's, this capability then tends to coincide with mission requirements. That infers that if we delay the beginning of our developments much further, then we'll be in the position where we would not be able to fulfill the forecast mission requirements when needed. For example, every year we delay, would tend to bring about a corresponding delay in power availability for any given mission.

Mr. MACKAY. In the earlier panel we heard discussions about the need for adequate shielding, and the need for adequate controls. It would appear to me that that's generic or state-of-the-art. We've got to be doing that no matter which design we choose. I gather if we choose one design it would give some companies advantages over others. I understand that.

Mr. ROSENBERG. In a generic sense the fact that the reactors will be launched in a dormant state inherently has safety built into it. The fact that the system would not be activated until it already achieved orbit would also be an added safety feature. The amount of radiation that would emanate from the reactor would not contaminate space itself. It's lower than what we get from solar flares. I don't think there's a major safety requirement that should preclude our being able to meet a 1990's type of schedule.

Dr. ARNOLD. If I may add, the areas of both shielding and the control of the reactor are, although important technologies, rather specific to the reactor design and to the payload, or the mission, if you will. I don't think that you can independently work in a generic sense on controls and shielding. It has to be part of an integrated reactor program.

Mr. MACKAY. There was another chart that had four phases: system studies, technology development, flight testing, et cetera.

Mr. ROSENBERG. This was the current SP–100 program (chart 3). It's geared to that same 10-year cycle and is compatible and consistent with it. We're now, all of us, in the system studies phase, and we've all said they will be completed by 1985 when a decision will be made. Some of the technology development ought to be started in 1984 leading to a ground demonstration. I don't believe that phase is funded. A program involving flight prototypes in the mid-1980's, leading to production by the 1990's is what this chart was intended to illustrate and this timing is compatible both with the capability of developing the reactor and with the mission requirements.

Mr. MACKAY. On that, how long could we go with a response that said all of the above from your other chart?

Mr. ROSENBERG. The timing is suitable to complete the system studies. There will be a need for funding in the 1984–85 time period to do additional technology development. I certainly would endorse what others have already said about some parallel work in the materials area. That's obviously one of the limiting technologies that need to be developed.

There has not been funding, of course, allocated for flight prototypes and production at this early stage of the game.

Mr. MACKAY. I guess in the case of the Congress and our staff, we may have been asking the same kind of mission definition questions you have. There's some irony in that, because we're not getting any answers either.

The question on your side of the table is how can we build toward something new that's not defined. The question on our side is how long do we pay for something with no definition of where we're headed?

Do I take the chart, space power sources, that we saw before as a limitation of the number of potential applications? Is that spelled out in the SP-100?

Mr. ROSENBERG. I don't believe the mission requirements are spelled out in the SP-100. These are missions that we believe are coming but which have not been fully defended. I'm sure there would be different opinions expressed from different agencies. For example, there were a number of studies that were conducted and concluded just recently on the potential requirements for a space station. General Electric participated in one study as a teammate of Gruman and Comsat. Those studies predominately had to do with what could be done with a space station, such as metal processing. I believe most of the eight studies concluded that there were important missions. Yet, at the same time, funding for a space station has been reduced and instead of maintaining any of the industry teams that were working on those studies, there is no funding for industry in the next fiscal year for further work. For me to say that in the year 2000 there definitely will be a space station which requires these power requirements is speculation. However, it is my inherent belief that we will ultimately have a space station, that we will ultimately be processing in space, and that we will be requiring these kind of power levels in order to do so.

Mr. MACKAY. I think I'm really saying the same thing Mr. Lujan is saying, which is: Why don't we define our problem that way and then say to you, develop the power source that would do this and would also give us back some flexibility for these other things?

Dr. DAHLBERG. The SP-100 program has a significant effort going on at JPL on mission analysis and requirements definition. Inputs from that are coming from NASA and the military. I think that that process probably hasn't had enough time to really jell into something.

Mr. MACKAY. Interesting way to make a decision.

Thank you, Madam Chairman.

Mrs. LLOYD. I think this is a triagency responsibility, in addition, it's funded by three agencies.

Mr. Volkmer?

Mr. VOLKMER. I have one additional question.

Do you see any technical problems arising from the reentry of a nuclear reactor that's been utilized?

Dr. WOLFE. I think that the object would be not to have the reactor reentry for hundreds of years.

Mr. VOLKMER. How are you going to keep it up there?

Dr. WOLFE. Well, if you get it into high enough orbit it stays up there for several hundred years, and in 300 years or so the radioac-

tivity in the reactor would be down by a factor of a thousand, roughly, over what it is when you immediately shut it down. If you do an analysis of even that kind of a reactor reentering the atmosphere the amount of radiation dose that would affect individuals would be absolutely negligible. That is, by that time the radioactivity will have died down sufficiently that allowing the reactor to enter the atmosphere and come down as dust would negligibly increase the radiation to human beings.

Dr. ARNOLD. Just to supplement what Dr. Wolfe said, I think he implies another criteria which is that the reactor will, in fact, disassemble and be widely dispersed when it does reenter.

Mr. ROSENBERG. The Soviet reactors which reentered the atmosphere were in orbits of approximately 150 nautical miles. Their theory of the case was to, boost them up into a higher orbit, when their useful life was expended. As you all know, they had two failures in this regard. We've also had our share of booster failures, from the earth as well as on one of the shuttle launches, so we're not immune to booster failures. On the other hand, I believe we can design a reactor if there were a requirement for low orbit missions that would disperse on reentry, breakup, and not enter as a solid mass in one area. They can be designed to disperse and dissipate the radiation levels to where they would be below any harmful levels.

Mr. VOLKMER. Some of us have a conceptual idea that if we go to a space station, that space station is going to be in GEO. It will be in low orbit. Hopefully it will be able to be utilized through the Shuttle to take materials back and forth, and if we use a reactor for that type it's going to be——

Mr. ROSENBERG. If there were to be a boost failure in trying to get it into a higher orbit then it would have to be designed so that it could be dispersed on reentry, and I believe that's technically feasible.

Mr. ANDERSON. On the SNAP-10A program, that was one of the critical issues—to assure that the reactor would disperse. We ran a test where a nonradioactive reactor and shield mockup was put into a suborbital condition and then allowed to reenter so we could see if the analytic models predicted the results. The reactor did, in fact, disperse the way we thought it would. That was one of the critical issues in the safety program.

Mr. VOLKMER. Disperse? But you're talking about dispersing of radioactive material then?

Mr. ANDERSON. Yes, but once it's dispersed, the amount of radiation would be realized over a wide enough area so that it would be a lower level of radiation than we now see in the normal atmosphere.

Mr. VOLKMER. In other words, nonharmful.

Mr. ROSENBERG. Nonharmful.

Mr. ANDERSON. By the way, the SNAP-10A system is in an orbit with a 3500-year life. It's not in a tumbling mode or anything else that would cause that orbit life to degrade lower. So it's in a very safe condition.

Mr. VOLKMER. But there could be a possibility that if you used one in low Earth orbit and if you wanted to take it out and replace

it, on a space station, would it be possible to put it on a rocket and send it out?

Dr. WOLFE. Send it out, certainly.

Mr. VOLKMER. Replace it with a new one and reactivate it?

Dr. WOLFE. I think that would be the plan, not to try and bring it back to Earth.

Mr. ROSENBERG. We would only need to disperse if there was a failure of the booster.

Mr. VOLKMER. Thank you, Madam Chairman.

Mrs. LLOYD. Mr. Lujan.

Mr. LUJAN. After looking at the charts I have a couple of questions. There's something that troubles me about leaving them up there for 300 or 400 years. I just feel uncomfortable.

Mr. ROSENBERG. You are correct, right now, there's something like close to 5,000 objects in orbit. The natural decay of the radioactive material, however, is such that in an orbit of 300 to 500 nautical miles they will normally decay over a period of 300 years, so there is no radiation danger.

Mr. LUJAN. I'm talking about even the nonnuclear. Just to leave it up there for—I'm talking about junk.

You're talking about that we're in the system studies phase now at $12 million a year, but you say that in 1984 we ought to go into the materials testing, technology development, and all of that. Does that mean that 1984 ought to have more than $12 million?

Mr. ROSENBERG. Yes; I would say that we would need additional dollars to begin the type of technology development that some of the other gentlemen have talked about.

Mr. LUJAN. What should we be looking at?

This is going to go down in our minds now as the figure that we need for 1984. [General laughter.]

Dr. WOLFE. I think to start this kind of a program you are typically talking about a starting program of $10 to $20 million, maybe more, to meaningfully start putting in facilities, building furnaces to get these refractory metals, putting in machines to——

Mr. LUJAN. Double the figure that we've got now.

Dr. WOLFE. Again, this is part of the ongoing program to define these, but those are rough numbers, I would think.

Mr. LUJAN. The other question that I had, as we were talking about what kind of power sources that we would use those that are in the lower requirements, like your land observation satellites, we wouldn't put reactors on the spacecraft.

Mr. ROSENBERG. No, we would not. It was not the intent of my chart to indicate that we would put reactors in spacecraft with low-power requirements. We would not. The chart did depict the growth of power requirements with time.

Incidentally, our four companies are not spending $12 million on system studies, we're spending $2 million. A great deal of that $12 million is going toward technology studies.

Mr. LUJAN. Is the answer then that the $12 million is sufficient for 1984, even with the technology.

Mr. ROSENBERG. I believe it is for 1984.

Dr. ARNOLD. I don't think it starts you toward the ground demo. You've then got to get going on some major facility studies and

eventually spend some money on facilities. That's going to take some engineering design work and planning.

Mr. LUJAN. Maybe what we're saying, then, is 1985 ought to be in the $20 to $30 million range as opposed to the $12 million.

One final thing, Mr. Rosenberg, that you said that kind of bothers me. When you were talking about the uses of a space station, you said "metals processing, pharmaceuticals, and all those other things." We always hear, "all those other things." But yet, I, as a member of the subcommittee that has oversight, have never heard what all of those other things are.

Mr. ROSENBERG. Well, I can mention a couple that have been looked at. The pharmaceuticals, of course, have been already studied and are planned for further study on the shuttle flights. The same is true for metal processing. The semiconductor area is another one where, the purity of the materials might be very, very beneficial. You want more specifics and I would be very happy to send the subcommittee a list of our findings on the mission studies that we did make.

Mr. LUJAN. I've asked NASA for this and never have gotten it. I'm aware of those two experiments, the materials processing and the pharmaceuticals, but one time they had some bees in there or something.

Mr. ROSENBERG. We'll see that a listing from our mission studies will be forwarded.*

Mr. LUJAN. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Lujan. I want to thank all of our witnesses today for the very excellent testimony. I think this has been a great hearing. I think everyone in this room will agree to that. We certainly learned a lot and I hope that we advanced the cause of space nuclear power systems today.

I would like to ask you if you would agree to answer questions that will be submitted in writing. We certainly couldn't cover all the areas we would like to cover this afternoon. I think perhaps we could have had 2 days of hearings on this very timely subject. We will be submitting questions to you and they will be made a part of the record. If there are no further questions the subcommittee is adjourned.

[Whereupon, at 4:49 p.m., the subcommittee was adjourned.]

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*Letter with requested information transmitted June 13, 1983.

APPENDIX

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of C:MDD:C-10699f

JUL 15 1983

Honorable Marilyn Lloyd
Chairman
Subcommittee on Energy Research
and Production
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Chairman Lloyd:

Enclosed are the responses to written questions, forwarded by your June 24, 1983, letter, resulting from the May 24, 1983, hearing at which Mr. Slone testified on Space Nuclear Power.

Our records indicate that this information completes the material requested during that portion of the hearing.

Sincerely,

Lynn W. Heninger
Acting Director,
Congressional Liaison Division

Enclosure

25th Anniversary
1958-1983

Questions submitted by Chairman Marilyn Lloyd during the May 24, 1983, hearing at which Mr. Slone testified on Space Nuclear Power.

QUESTION 1:

Your testimony suggests that Lewis has, or is in the process of, letting a contract for multi-megawatt power systems study. What are NASA's mission drivers for such studies? What is the status of this activity?

ANSWER 1:

The Lewis Research Center (LeRC) is in the process of letting a contract for a multi-megawatt power system study. At present, the study is not mission specific but is a generic study of these large nuclear space power systems leading to conceptual designs of potentially attractive systems. Hopefully, the results of this study will allow us to identify viable reactor and energy conversion concepts, the physical (size and mass) and operational characteristics for these systems, and the enabling technologies required for their development.

In addition, we would examine the launch vehicle capabilities required by these large space power systems. This information will allow us to assess the feasibility of developing these power systems and to lay out a development plan for them that could be implemented should specific mission needs be identified.

At present, the review team is in the final steps of technical evaluation of the proposals.

QUESTION 2:

In your testimony, you mentioned that you will be looking at facilities other than the Space Power Facility (SPF). Could you elaborate some on this aspect? What other facilities are being considered and for what activities would these facilities be used?

ANSWER 2:

At present, LeRC is only evaluating the potential of the Space Power Facility for use in testing any future ground engineering systems. Within the context of the SP-100 program, the Department of Energy is performing a survey of other facilities that could possibly be used for such tests if they are deemed necessary. The data on each of these facilities will be assembled. Once the ground engineering systems requirements are identified, a separate committee will evaluate the applicability of each of these facilities (including the Space Power Facility) for meeting these requirements.

QUESTION 3:

What has been the funding level at Lewis for space nuclear power related work; i.e., prior years, FY 1983 and FY 1984? Do you receive funding from DARPA in support of your mission analyses or systems definition work?

ANSWER 3:

In the late 1960's and early 1970's, nearly $200 million was spent at Lewis for space nuclear power development. In the present program, LeRC's funding levels are FY 1982 ($100,000 plus 6 man years), FY 1983 ($580,000 plus 12 man years), FY 1984 (est. $1.1 million plus 12 man years). The only funding that NASA presently receives from DARPA for the SP-100 program is $60,000 per year to be used for reimbursable travel funds.

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
Upton, Long Island, New York 11973

(516) 282-
FTS 666- 2440

Department of Nuclear Energy
Building 820M

July 11, 1983

Ms. Julie Shisler
Room B-374
Rayburn House Office Building
Washington, D.C. 20515

Dear Ms. Shisler:

Enclosed are the responses to the additional questions Congresswoman Lloyd sent last week. I am writing for Dr. Kouts. A copy of the original questions and the request letter is enclosed.

Sincerely,

James Powell

James R. Powell

JPR:jd
Enclosure

1. At BNL, we have facilities to conduct non-nuclear tests related to development of particle bed reactors. These would include thermal-hydraulic and compatibility experiments on simulated reactor cores operating at prototype conditions. (These cores would be heated electrically rather than nuclearly.) For tests involving nuclear performance, we would work with companies and laboratories with the requisite facilities, i.e., GA Technologies, INEL, ORNL, etc., as appropriate.

We propose a demonstration of a non-nuclear integrated reactor/power conversion system, using electrical heating of the particles to simulate the nuclear heating. All of the thermal-hydraulic compatibility and integration aspects of an actual full system would be demonstrated with such an experiment. The proposed demonstration, together with the extensive irradiation experience on TRISO HTGR fuel and criticality experiments at an appropriate laboratory, would provide sufficient information for proceeding with a ground-based demonstration reactor and power conversion system.

Before carrying out the integrated non-nuclear demonstration, smaller scale experiments relating to compatibility of reactor materials and thermal-hydraulic performance would be carried out. This will include extended tests of candidate frit materials with the fuel particles, and confirmation of analytical predictions of thermal-hydraulic behavior.

With regard to integration with power conversion systems, particle bed reactors fit extremely well with gas Brayton cycles, and these have been proposed. Other power conversion options also appear feasible, including thermoelectrics and thermophotovoltaics. Thermionics probably require too high a temperature to be practical. Rankine-Brayton cycles (e.g., boiling potassium)

could be used in principle, but would require an intermediate heat exchanger between the FBR gas coolant and the power conversion cycle.

2. Yes, the Fixed Bed Reactor could be easily scaled down to lower power. For low powers, we would prefer designs in which the HTGR fuel particles were placed in a number of sub-elements in a matrix of ZrH_2. The FBR would operate in the closed-cycle mode with coolant gas (helium, helium-xenon, or some other inert gas) at exit temperatures up to ~1500 degrees Kelvin.

The size of lower power FBR's will be determined by neutronics considerations rather than power level. Studies indicate that the smallest practical reactor will be approximately 11 inches in diameter and about 150 kg in total weight. Such a reactor would operate at any desired power level up to 250 kW(e) for extended periods, i.e., 7 years.

3. I thought the National Academy Symposium was very useful in a number of ways. It brought together the reactor technologists and the potential users; it served to collect and sum up the state-of-the-art in space reactors; and it provided a feeling that the field was about to waken from its domant state. To my knowledge, there were no major new technical findings or policy recommendations out of the meeting, but none would be expected, given that the space nuclear program was just getting started again. I have not seen the report of the NAS committee and cannot comment on that.

REFER TO:
GHF-83-44

Westinghouse Electric Corporation
Advanced Power Systems Divisions

Advanced Energy Systems Division
Madison Pennsylvania 15663-0158

July 11, 1983

Ms. Julie Shisler
Room B-374
Rayburn House Office Building
Washington, D.C. 20515

SUBJECT: HEARINGS ON SPACE NUCLEAR POWER

Dear Ms. Shisler:

Attached are responses to the questions contained in the Honorable Marilyn Lloyd's letter of June 24, 1983 relating to Dr. W.H. Arnold's Testimony on Space Nuclear Power.

Very truly yours,

G.H. FARBMAN, Manager
Program Development

/bls

Attachment

RESPONSES TO ADDITIONAL QUESTIONS

BY

DR. W. HOWARD ARNOLD

WESTINGHOUSE ELECTRIC CORPORATION

RELATED TO

HEARING ON SPACE NUCLEAR POWER
BEFORE THE

SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION
SUBCOMMITTEE ON SPACE SCIENCE AND TECHNOLOGY
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

QUESTION 1: AT ONE TIME, I UNDERSTAND THAT YOU FOUND IT DIFFICULT TO CONVINCE PEOPLE THAT ENERGY CONVERSION SYSTEMS FOR SPACE USE THAT REQUIRED ROTATING MACHINERY COULD PERFORM WITH SUFFICIENT RELIABILITY. IS THIS STILL THE SITUATION?

ANSWER: *THE USE OF ROTATING ENERGY CONVERSION MACHINERY IS ONE OF THE OPTIONS AVAILABLE FOR SPACE NUCLEAR POWER SYSTEMS. WESTINGHOUSE IS EVALUATING THEM, IN PARALLEL WITH STATIC THERMOELECTRIC SYSTEMS, TO TRY TO DEFINE THE RELATIVE RELIABILITIES, DEVELOPMENT NEEDS, AND COST EFFECTIVENESS OF THE ALTERNATIVE SYSTEMS. IT IS CLEAR THAT THE LONG-TERM RELIABILITY OF ROTATING MACHINERY STILL REMAINS AN ITEM OF CONCERN. THE EXPERIENCE THAT THE NASA LEWIS RESEARCH CENTER HAS HAD IN DEMONSTRATING OVER 40,000 HOURS OF SUCCESSFUL OPERATION OF A BRAYTON ROTATING UNIT BODES WELL FOR THE POTENTIAL RELIABILITY OF DYNAMIC MACHINERY. IF ROTATING MACHINERY WERE ADAPTED FOR SPACE APPLICATION, IT WOULD OF NECESSITY REQUIRE ADDITIONAL TEST AND DEMONSTRATION TO DEVELOP ADEQUATE CONFIDENCE IN CYCLE RELIABILITY.*

QUESTION 2: IF MORE FUNDS WERE AUTHORIZED FOR THIS PROGRAM IN 1985, DO YOU HAVE A CADRE OF EXPERTS AND FACILITIES THAT COULD BE MADE AVAILABLE TO THE PROGRAM?

ANSWER: *WESTINGHOUSE IS PREPARED TO SUPPORT THE SP-100 PROGRAM TO WHATEVER EXTENT IS NEEDED TO MEET ANTICIPATED 1985 PROGRAM NEEDS. AN IN-HOUSE EFFORT HAS BEEN UNDERWAY FOR THE LAST TWO YEARS TO BUILD UP THE EXPERTISE OF A GROWING CADRE OF SPECIALISTS IN SPACE NUCLEAR POWER SYSTEMS TECHNOLOGIES. THIS "TRAINING" EFFORT HAS BEEN LED BY ENGINEERS AND MANAGERS WHO HAVE HAD RESPONSIBLE POSITIONS IN THE NERVA, SNAP, AND OTHER AEROSPACE RELATED NUCLEAR PROGRAMS. THE EXPANDING CAPABILITY OF THIS CADRE HAS BEEN EXERCISED BY INTERNALLY FUNDED STUDIES ON COMPACT NUCLEAR POWER PLANTS OVER A WIDE RANGE OF RATINGS AND BY PARTICIPATION IN THE SP-100 SYSTEM STUDIES AND DEVELOPMENT PROGRAM PLANNING ACTIVITIES. UPON THE ACCELERATION OF THE SP-100 PROGRAM, THIS CADRE OF SPACE NUCLEAR SYSTEM EXPERTS WILL BE ABLE TO CALL UPON AND DIRECT THE EFFORTS OF THE ENGINEERS AND SCIENTISTS DRAWN FROM THE VARIOUS AREAS OF EXPERTISE WITHIN OUR ENGINEERING AND TECHNOLOGY ORGANIZATIONS.*

WITH RESPECT TO FACILITIES, WESTINGHOUSE CAN ALSO STATE THAT IT IS PREPARED FOR A MORE EXTENSIVE EFFORT, STARTING IN 1985 OR EARLIER. THE FACILITY FOR THE DEVELOPMENT AND TESTING OF REFRACTORY METAL ALLOYS IS FULLY OPERATIONAL TODAY. THE LABORATORY CAPABILITIES FOR FUEL DEVELOPMENT, TRIBIOLOGICAL TESTING, VIBRATORY TESTING, AND RELATED SPECIAL TESTING AND ANALYSIS ACTIVITIES CAN BE MADE AVAILABLE TO THE PROGRAM NOW. THE ENGINEERING FACILITIES, SUCH AS COMPUTER ASSISTED DESIGN (CAD), CENTRALIZED HIGH SPEED COMPUTERS, HYBRID ANALOG-DIGITAL COMPUTER ANALYSIS, AND LOCAL COMPUTER TERMINALS ARE FULLY SUITABLE FOR THE ANTICIPATED WORK. REMOTE SITE FACILITIES FOR SYSTEMS TESTS DO NOT CURRENTLY EXIST, AS INDICATED IN MY TESTIMONY.

IN SUMMARY, WESTINGHOUSE IS FULLY CAPABLE OF PROVIDING THE RESOURCES REQUIRED TO MEET THE EARLY PHASE OF AN ACCELERATED SP-100 PROGRAM IN 1985 OR, IF DESIRED, IN 1984.

QUESTION 3: ARE THERE UNRESOLVED SPACE REACTOR SYSTEMS SAFETY ISSUES THAT MUST BE ADDRESSED WITHIN THE FRAMEWORK OF THE PRESENT SP-100 PROGRAM? DO YOU WORK ON SPECIFIC SAFETY-RELATED R&D PROJECTS THAT ARE APPLICABLE TO THIS PROGRAM?

ANSWER: *SAFETY IS CONSIDERED TO BE OF PARAMOUNT IMPORTANCE IN THE APPLICATION OF NUCLEAR REACTORS TO SPACE MISSIONS. THE COMBINED HERITAGE OF SAFETY-CONSCIOUSNESS IN BOTH THE COMMERCIAL NUCLEAR POWER INDUSTRY AND THE MANNED SPACE PROGRAMS HELPS TO ASSURE THAT SAFETY-RELATED ISSUES, ANALYSES, AND DESIGN APPROACHES WILL BE IN THE FOREFRONT OF THE PROGRAM.*

DURING THIS EARLY PHASE OF THE SP-100 PROGRAM, THE NUCLEAR SAFETY REQUIREMENTS USED FOR CONCEPTUAL DESIGN ACTIVITIES ARE CONTAINED IN DOE's "NUCLEAR SAFETY CRITERIA AND SPECIFICATIONS FOR SPACE NUCLEAR REACTORS," OSNP-1, REV. 0, DATED AUGUST 1982. THE MAJOR UNRESOLVED SAFETY ISSUES THAT MUST BE ADDRESSED, IN ORDER TO ASSURE COMPLIANCE WITH BOTH THE LETTER AND SPIRIT OF THE SAFETY CRITERIA, RELATE TO PROTECTION OF THE PUBLIC IN THE EVENT OF A LAUNCH MISHAP OR INADVERTENT RE-ENTRY OF AN ORBITING POWER STATION. THE LAUNCH MISHAPS REQUIRE RESOLUTION OF ISSUES RELATING TO MAINTAINING SUB-CRITICALITY OF THE REACTOR UPON IMMERSION IN WATER, IF LAUNCH ABORT RESULTS IN SYSTEM INUNDATION, OR UPON COMPACTION, IF LAUNCH FAILURE RESULTS IN GROUND IMPACT. THE INADVERTENT RE-ENTRY REQUIRES ASSURANCE THAT THE REACTOR WILL DISASSEMBLE AND BURN-UP IN THE UPPER ATMOSPHERE, SO THAT AN UNACCEPTABLE CONCENTRATION OF FISSION PRODUCTS CANNOT ENTER THE BIOSPHERE. THESE, AND OTHER ISSUES RELATING TO CONTROL, REDUNDANCY, AND EMERGENCY COOLING, WILL REQUIRE CONSIDERABLE EFFORT FOR RESOLUTION; THE GROUNDWORK FOR RESOLUTION MUST BE UNDERTAKEN DURING THIS EARLY PHASE OF THE PROGRAM.

WESTINGHOUSE EXPERIENCE AND ACTIVITIES IN NUCLEAR PLANT SAFETY FOR PRESSURIZED WATER REACTORS, LIQUID METAL COOLED REACTORS, AND GAS COOLED SPACE REACTORS (ERVA) ALL CONTRIBUTE TO AN EXPERTISE IN THE SPACE NUCLEAR SAFETY AREA. THE SYNERGISM BETWEEN THE SAFETY ISSUES OF LIQUID METAL COOLED FAST REACTORS AND THE SMALL FAST REACTORS CONTEMPLATED FOR SPACE APPLICATION MAKES THE CURRENT LMFBR SAFETY RELATED R&D ACTIVITIES PARTICULARLY APPLICABLE.

QUESTION 4: ARE THE TIMETABLES OUTLINED IN THE SP-100 AGREEMENT ADEQUATE TO EXPLORE ALL VIABLE OPTIONS REGARDING NUCLEAR REACTOR SYSTEMS?

ANSWER: *THE TRI-AGENCY AGREEMENT IMPLIES A TIME-TABLE TO REACH THE DECISION TO PROCEED WITH GROUND DEMONSTRATION OF A NUCLEAR SPACE POWER SYSTEM BY THE END OF FY-85. WE BELIEVE THIS TIME-TABLE PROVIDES ADEQUATE OPPORTUNITY TO EXPLORE VIABLE OPTIONS AND TO SELECT A NUCLEAR SPACE POWER SYSTEM CONCEPT APPROPRIATE FOR SUCH DEVELOPMENT AND DEMONSTRATION. WE ALSO BELIEVE THAT INCREASED TECHNOLOGY DEVELOPMENT ACTIVITIES, SUCH AS IN DEVELOPING REFRACTORY ALLOYS, IN PARALLEL WITH THE CONCEPT SELECTION PROCESS CAN LEAD TO A MORE TIME AND COST EFFICIENT OVERALL PROGRAM, THROUGH MITIGATING THE POTENTIAL FOR DELAYS DURING THE MORE COST INTENSIVE GROUND DEMONSTRATION PHASE.*

GA Technologies

GA Technologies Inc.
P.O. BOX 81608
SAN DIEGO, CALIFORNIA 92138
(619) 455-2080

HAROLD M. AGNEW
President

June 30, 1983

Honorable Marilyn Lloyd
House of Representatives
Congress of the Unites States
2334 Rayburn House Office Bldg.
Washington, D. C. 20515

Attention: Ms. Julie Shisler
Room B-374
Rayburn House Office Building
Washington, D. C. 20515

Dear Ms. Lloyd:

With reference to your letter of June 24, 1983, containing additional questions relating to our testimony of May 14 on Space Nuclear Power, I am happy to forward the following answers.

Q. If more funds were authorized for this program in 1985, do you have a cadre of experts and facilities that could be made available to the program?

A. Yes. We have between five and ten experts working on space power programs at the moment and this could be increased by a factor of ten with some modest adjustments in our other programs. Laboratories and irradiation facilities (TRIGA) for a large program are also readily available.

Q. Are there unresolved space reactor systems safety issues that must be addressed within the framework of the present SP-100 program? Do you work on specific safety-related R&D projects that are applicable to this program?

A. We do not feel that there are unresolved safety issues that must be addressed within the SP-100 program. There are many safety issues but our studies indicate that their solution will result from normal engineering design effort.

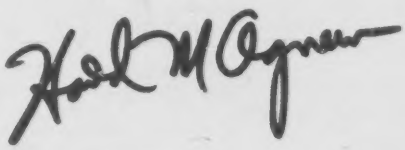
We do not have any specific safety related R&D projects underway; rather, safety requirements are defined and resolved as part of our normal design activities.

Q. Are the timetables outlined in SP-100 agreement adequate to explore all viable options regarding nuclear systems?

Yes. We believe that the viable options for space nuclear power systems have been identified, that a significant technology base exists for each option, and that efficient flight systems could be in orbit before the early 1990s if such a need should arise.

I appreciate very much your interest in this very vital subject area. In my opinion, the United States needs to have a capability to provide nuclear power systems for future space needs. If I can supply further information, please let me know.

Sincerely,



cc: N. E. Carey
GA Technologies
Washington, D. C.

MARILYN LLOYD
3RD DISTRICT, TENNESSEE

COMMITTEES
ARMED SERVICES
SCIENCE AND TECHNOLOGY
SELECT COMMITTEE ON AGING

Congress of the United States
House of Representatives
Washington, D.C. 20515

2334 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, D.C. 20515
TELEPHONE: (202) 225-5771

903 JOHN DOLOMON FEDERAL OFFICE BUILDING
CHATTANOOGA, TENNESSEE 37401
TELEPHONE: (615) 267-0160

1211 FEDERAL OFFICE BUILDING
OAK RIDGE, TENNESSEE 37830
TELEPHONE: (615) 576-1277

June 24, 1983

Robert E. Harris, Director
Energy Systems
Rockwell International
1745 Jefferson Davis Highway
Arlington, Virginia 22202

Dear Mr. Harris:

Attached are additional questions related to your testimony and the hearing on Space Nuclear Power held on May 14, 1983. I would appreciate receiving your responses on or before July 11, 1983, so that they may be included in the published hearing record. Please forward this information to Ms. Julie Shisler, Room B-374, Rayburn House Office Building, Washington, D.C. 20515.

Should you have any questions regarding this matter please contact Mr. Nelson Milder of my Subcommittee Staff at (202) 225-5378.

Sincerely yours,

Marilyn Lloyd

MARILYN LLOYD
Member of Congress

ML:Mlk
Attachment

1. If more funds were authorized for this program in 1985, do you have a cadre of experts and facilities that could be made available to the program?

2. Are there unresolved space reactor systems safety issues that must be addressed within the framework of the present SP-100 program? Do you work on specific safety-related R&D projects that are applicable to this program?

3. Are the timetables outlined in SP-100 agreement adequate to explore all viable options regarding nuclear systems?

Rockwell International
Energy Systems Group

ANSWERS TO QUESTIONS FROM MAY 14, 1983, HEARING ON SPACE NUCLEAR POWER

Question 1

If more funds were authorized for this program in 1985, do you have a cadre of experts and facilities that could be made available to the program?

Rockwell currently employs over 150 personnel with 1100 person-years of applicable space nuclear power system experience. At the present time, about a dozen of these personnel are working on Rockwell's activities for the SP-100 Program. In addition, we have assigned several young personnel to these activities and are using our own funding to "transfer technology" to these personnel. Many more such qualified personnel are not only available but anxious to begin working on this evolving and exciting program.

In a similar manner, there are a multitude of facilities which could be made available in FY 1985. The government-owned facilities complex at Rockwell's Santa Susana Field Laboratory (SSFL) and at the Energy Technology Engineering Center (ETEC - which Rockwell operates for the DOE) was constructed and used for the development and testing of the SNAP compact space nuclear reactor systems from the late 1950s through early 1970s. The nation's first operational space reactor electric system, SNAP-10A, was developed and tested at the facilities prior to launching in 1965 from the Vandenberg Air Force Base in California. Development and testing of more advanced, higher powered systems, SNAP-2 and -8 continued at these facilities until the early 1970s. During this 15-year period six space reactors were developed and tested from 65 kWt to 1000 kWt at temperatures from 1000°F to 1300°F.

Situated on an adjacent parcel of land is Rockwell's hot cell facility. This facility--the largest privately owned facility of its kind in the free world--is fully operational today and could be used for interim examination of nuclear subsystem tests.

Question 1 (Continued)

With availability of program funding during FY 1985, these nuclear and non-nuclear facilities can be prepared for development and testing of advanced space nuclear reactor subassemblies and subsystems as required to fulfill initial program objectives. Within an approximate radius of 100 miles from the facilities are located many West Coast industries and other government-sponsored space technology and development facilities such as the Jet Propulsion Laboratory, California Institute of Technology, and Vandenberg Air Force Base. Rockwell's Space Transportation Group (builders of the Space Shuttle) is also located in nearby Downey, Califoria.

There are multiple facilities available to perform reactor testing, shield testing, liquid metal testing, and structural testing. Five key facilities are discussed below as good examples of our testing capabilities.

Building 024

This government-owned facility contains two underground reactor test vaults 15 by 15 by 19 feet high and an auxiliary vault between the two which is 15 by 26 by 19 feet high. Each of the reactor test vaults can contain an 8-feet diameter by 15-feet high vacuum chamber for enclosure of the nuclear system during long duration developmental testing at design-rated temperatures and power levels up to 10 Mwt. (Note: This is based upon test operations data from the SNAP program extrapolated to higher power levels. This information was obtained during preliminary assessment of the facility to determine capability of existing shielding.)

This facility is in standby and can be prepared to accept space nuclear reactor critical assemblies and/or developmental space reactors for power testing during FY 1985. Funding levels and procurement of long lead items should be identified during FY 1984.

Question 1 (Continued)

Building 059

This government-owned facility contains an underground reactor test vault 12 by 12 by 15 feet high, a vacuum piping vault 21 by 27 by 15 feet high, and an auxiliary vault 28 by 39 by 27 feet high. The reactor test vault can accommodate an 8-feet-diameter by 15-feet-high vacuum chamber for enclosure of the nuclear subsystem during long duration qualification testing at design-rated temperatures and power levels of more than 10 Mwt. (Note: The SNAP 8 reactor and radiation shield subassembly were tested at a power level of 1 Mwt and a temperature of 1300°F for 7000 hours in a 5-feet-diameter by 10-feet-high vacuum chamber in the test vault in this facility.)

This facility is in standby and can be prepared to accept space nuclear reactor and radiation shield subsystems for developmental testing during FY 1985. Funding levels and procurement of long lead items should be identified in FY 1984.

Building 019

This government-owned facility is specifically designed for zero-power testing of completely assembled compact space reactors. The facility contains a 9-foot-diameter by 17-foot-high vacuum chamber which can be lowered by a hydraulic ram into a shielded 40-foot-deep underground vault. Loading of the reactor core, final assembly, and checkout of the reactor controls can be performed in this facility. The vacuum chamber enables testing of the assembled reactor at zero-power and operating temperatures to determine temperature coefficients and excess reactivity and permits shimming prior to full-power testing or launch.

This facility is in standby and can be prepared to accept space reactor subsystems for final assembly and zero-power testing during FY 1985. Funding levels for procurement of long lead items should be identified in FY 1984.

Question 1 (Continued)

Building 020

This hot cell facility, used for examination of highly radioactive materials. is wholly owned by Rockwell. It is the largest privately owned facility of its type in the free world.

Post-test examination of the SNAP-2, -8, and -10A reactor cores was performed in this hot cell facility. A multitude of other examinations and operations have been and are performed in the hot cells on a routine basis.

The hot cell is located close to the other test facilities (~1/2 mile) within the boundary of the same test complex. This provides a powerful tool for testing coupled with interim examinations to obtain early data on nuclear core performance.

The hot cell facility is currently in full operation and is fully staffed. The facility can be made available to the SP-100 program at any time the need arises.

Building 042

This government-owned facility was specifically used to fabricate lithium-hydride neutron shields for space reactor electric systems. The facility contains specially modified furnaces for casting shields. The furnaces control hydrogen and temperature environments and were used in the past to successfully cast shields up to 6 feet in diameter.

The facility is in a partial standby condition and can be prepared for checkout castings in less than one year.

Rockwell believes our facilities to be some of the finest and most applicable to the space nuclear power program. The facilities discussed here and many other facilities are available any time for a walking inspection at the SSFL and ETEC, located 15 minutes from Rockwell Energy Systems Group Headquarters in Canoga Park, California.

Rockwell International
Energy Systems Group

ANSWERS TO QUESTIONS FROM MAY 14, 1983, HEARING ON SPACE NUCLEAR POWER

Question 2

Are there unresolved space reactor systems safety issues that must be addressed within the framework of the present SP-100 Program? Do you work on specific safety-related R&D projects that are applicable to this program?

For clarity, this is answered as two separate questions. The first answer concerns the unresolved space reactor systems safety issues.

There are several safety issues that must be addressed during the present SP-100 Program. We do not classify these issues as unresolved, because they do not represent technology roadblocks that could delay or jeopardize a follow-on system development program. The issues result from the Department of Energy safety criteria applied to the program; namely, OSNP-1 (Revision 0), "Nuclear Safety Criteria and Specifications for Space Nuclear Reactors, August 1982." The two key safety issues resulting from these requirements are:

1. The reactor must remain subcritical (i.e, not capable of sustaining a nuclear chain reaction) when immersed in water or other fluids,

2. Radioactive material must be safety dispersed during reactor system reentry to the atmosphere.

Although the specific details of a reactor system design which would be required to resolve these issues has not been finalized, our experience tells us that these issues are amenable to normal engineering design solutions.

The first key issue results from the requirement of a launch abort, where the reactor remains intact and becomes surrounded by and filled with water or another fluid (such as a propellant). To assure subcriticality in such a condition, the reactor may be required to contain nuclear-absorbing "poisons" or

Question 2 (Continued)

other poisoning mechanisms. These would in turn be designed to survive the launch abort environment. Because these poisons or mechanisms could preclude reactor startup in space, mechanical or other methods may be required to remove them prior to actual reactor startup. This subcriticality philosophy is different than that employed for the launch of SNAP-10A. This reactor would not have been subcritical in water. However, the energy release in a water immersion and flooding situation was intrinsically bracketed by the physics and mechanical design of the reactor, and the energy release was actually determined from a full-size destructive test.

The second key issue results from the requirement to protect the populace if the reactor should reenter the earth's atmosphere. Such reentry is unlikely, but could be postulated to occur after the reactor has been operated and has a radioactive inventory. Design engineering would be done to assure that the reactor breaks up and disperses during the reentry process. This was a key engineering development activity for Rockwell during design of the SNAP-10A reactor system which was launched in 1965. The dispersal requirement poses design restrictions on fuel forms, fuel cladding, reactor containment, and reactor controls. As we learned in the past, certain designs enhance the burnup and dispersal action.

Again, we wish to reiterate that we do not believe there are unresolved issues at this time which would preclude launching and operating a space reactor electric system. There are engineering problems which require engineering solutions.

We now return to the second part of this question which concerned our applicable safety-related R&D projects.

Rockwell is actively engaged in R&D projects which are directly usable in the SP-100 Program. These projects are part of the Liquid Metal Fast Breeder Reactor safety program. Other Rockwell safety activities are also directly

Question 2 (Continued)

applicable to SP-100 and include reentry heating analysis, structural loading analysis, and launch vehicle analysis.

Rockwell, through its Atomics International Division, has been actively engaged in nuclear safety design and R&D for over 25 years. Our early involvement started in space nuclear power and commercial nuclear power development. Atomics International was responsible for the Aerospace Safety Program that supported the launch of the SNAP-10A reactor system. As such, AI was responsible for helping to evolve today's safety philosophy for reactor systems in space.

Our safety activities in commercial nuclear power have evolved to the present where we perform a full spectrum of analyses for LMFBR safety. This includes accident prevention, benign accident termination, core dispersal accident analyses, and risk assessment analyses. We are currently designing LMFBRs to avoid common cause failures. This important safety activity is based on operating experience in the nuclear industry which we are using to develop theoretical models for common cause failures. AI is also actively engaged in emergency core heat removal R&D, inherent shutdown system R&D, and R&D on core behavior under accident conditions. Key safety areas where our efforts are intimately related to space reactor systems are liquid metal fire behavior (relating to dispersal of liquid metals during a launch abort), radiological aerosol behavior, and risk assessment.

Rockwell is deeply involved in this country's safety program for the LMFBR and in safety programs for the Space Transportation System. These activities are directly applicable to the SP-100 Program, and Rockwell has the manpower, the experience, and the know-how needed to support this program.

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Rockwell International
Energy Systems Group

ANSWERS TO QUESTIONS FROM MAY 14, 1983, HEARING ON SPACE NUCLEAR POWER

Question 3

Are the timetables outlined in the SP-100 agreement adequate to explore all viable options regarding nuclear systems?

The SP-100 timetable identified two major milestones:

1. An intermediate review (in March 1984) to review program progress and adjust the ground test phase decision as needed.

2. A ground test phase decision in July 1985 which will, in turn, establish FY 1986 and out-year budgets.

Investigations exploring potential nuclear systems for SP-100 are now underway at several industrial contractors, national laboratories, and NASA facilities. Rockwell believes that the program milestones can be supported--and all viable options investigated--on the timetable currently in place.

However, as we noted several times in our testimony, the key ingredient in making the timetable meaningful is the establishment of real mission needs. From these needs follow the mission requirements and system design requirements. The direction and cohesiveness of the program follows logically from the identification of these mission needs. Without the identified needs, the program runs the risk of lapsing into a "technology development for technology sake" syndrome.

Program funding appears adequate--at this time--to support the program timetable, again assuming a real mission need is identified. If, however, a mission need date requires that facilities be readied or generic technology development (i.e., fuels, materials, shields, etc.) activities be started earlier than FY 1986, additional funds beginning in FY 1984 would be necessary.

8100A/amm

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY . . . . . VALLEY FORGE SPACE CENTER
(MAIL: P. O. BOX 8555, PHILADELPHIA, PENNSYLVANIA 19101), Phone (215) 962-2000

SPACE SYSTEMS DIVISION

July 5, 1983

Ms. Julie Shisler
Room B374
Rayburn House Office Building
Washington, D.C. 20515

Dear Julie:

Attached, in response to the Honorable Marilyn Lloyd's request, are the answers to additional questions related to Mr. A. J. Rosenberg's testimony and the hearing on Space Nuclear Power.

If I may be of any further assistance please do not hesitate in contacting me.

Very truly yours,

E G Wolfram

E. G. Wolfram, Manager
Division Planning & Strategy Analysis

/bjp
attachment

SP-100 Subcommittee Questions and Answers

Q. If more funds were authorized for this program in 1985, do you have a cadre of experts and facilities that could be available to the program?

A. General Electric has the experts and facilities available to the SP-100 program at the Space Systems Division, Advanced Reactor Systems Department and Advanced Energy Programs Department. Each of these components has decades of experience in developing, building and operating equipment in the specific technology areas required for the SP-100 program. The personnel in these areas are completely competent in the disciplines related to the program and GE could move quickly in response to an acceleration of the schedule that would result with increased funding. There are currently 52 GE experts working on the SP-100 study, 30 with more than 700 man-years of nuclear experience and 22 with more than 400 man-years of space experience. This core of experts can be expanded 10-fold within General Electric with increased funding and the timely release of those funds when the demands of the program require it.

Q. Are there unresolved space reactor systems safety issues that must be addressed within the framework of the present SP-100 program? Do you work on specific safety-related R&D projects that are applicable to this program?

A. Under the present SP-100 program there are no unresolved systems safety issues that cannot be met by the space nuclear reactor safety criteria established by the U.S. government and the United Nations. In brief, those criteria are:

(1) Launch an appropriately shielded reactor in a subcritical mode,

(2) Design it so as to prevent criticality at or after impact should the subcritical reactor reenter before start-up, and

(3) Limit start-up until the system achieves an earth orbit of sufficient duration to provide time for fission product decay to safe levels.

General Electric has a continuing history of safety-related R&D projects which are applicable to the SP-100 program. These include the safety side of Liquid Metal Fast Breeder Reactors which we are studying and testing in connection with LMFBR fuel. We have also developed special containment techniques for space nuclear isotope systems. GE containment designs for these systems, radioactive at launch, have been thoroughly proven through analysis, rigorous and careful testing and have been demonstrated safe in actual space flight. The same expertise and capability associated with reactors and isotopes would be applied to the SP-100 program.

Q. Are the timetables outlined in the SP-100 agreement adequate to explore all viable options regarding nuclear systems?

A. As I indicated in my testimony, it will take about a decade to complete the development of a safe space nuclear reactor and I believe we should start now on the technology development phase if we are to meet the projected mission needs of the 1990's. There are no technology breakthroughs required, however technical and engineering development must be diligently and carefully pursued to assure a sound design solution.

Right now, the SP-100 program is in a conceptual decision phase. Many options are available: Reactor type; conversion system approach; heat transport and rejection methods. Careful scrutiny is required to sort out the options and the approach or approaches offering the "Best" performance with the highest probability of success. In essence, the best balance between performance needs, schedule, technical risk and funding available must be chosen. Certain common

technologies such as the development of refractory metals and their manufacturing techniques should and can proceed now; other technology developments require subsystem and configuration decisions. The current program plan is designed to attack the problem of system selection in an orderly manner. The basic plan includes a reassessment of the major program milestones in March of 1984. At that time the initial mission studies and conceptual studies will have been completed and some of the key technology developments will be under way. In my opinion, there is a sound logic to this approach. Funding levels can always be a source of debate and more money could be wisely spent. The current question is whether a better or earlier decision will result by the infusion of significantly more funds. The answer to that seems to me to be "not at this time", however, additional funds for technology will reduce the risk of a successful completion.

Madame Chairperson under the SP-100 program, a large community of technologists are currently studying the problem of placing a significant power source in space, based on a nuclear thermal source. Three government agencies are placing significant resources on the task. Lewis Research Center, the Jet Propulsion Laboratory and the Los Alamos National Laboratory all have significant efforts underway. In addition, at least four industry contractors are carrying out studies, examining the available approaches for a space nuclear power supply. With that kind of effort and with the current plan in place, I believe that there is sufficient time and resources to make a proper system selection.

GENERAL ELECTRIC
COMPANY
SPACE SYSTEMS DIVISION
VALLEY FORGE SPACE CENTER
P. O. BOX 8555 PHILADELPHIA, PA. 19101

A. J. ROSENBERG
VICE PRESIDENT AND
GENERAL MANAGER

June 13, 1983

The Honorable Marilyn Lloyd
U. S. House of Representatives
Washington, D.C.

Dear Congresswoman Lloyd:

It was an honor and privilege for the General Electric Co. to testify before your Subcommittee on the critically important topic of Space Nuclear Power. I feel, as I'm sure you do, that if this country's future civil and military space missions are to become a reality, high power will have to be part of those missions.

During my testimony, as you will recall, the subject of potential uses of the Space Station came up and I presented two specific potential uses in the area of Industrial processing; namely, metals processing and pharmaceutical development. I also indicated that there were others and Congressman Lujan specifically asked, "What were the others?" The following is a list of processes that requires high power and would benefit from the space environment on board the Space Station.

A. Production of Mercury Cadmium Tellurium (HgCdTe) for Radiation Detection Systems
B. Production of Bulk Gallium Arsenide (GaAs) for the Semiconductor Industry
C. Production of Thin Film GaAs for the Semiconductor Industry
D. X-Ray Target Production for the Medical Diagnostics Industry
E. Containerless Melting of Glass for Fabrication of Fiber Optics used in the Communication Industry
F. Crystal Growth for various Laser Application

These items are representative of those areas which could have commercial payoff. The power levels will increase substantially when multiple processes are set up in parallel to take advantage of larger production runs. Thank you again.

Very truly yours,

A. J. Rosenberg
Vice President and General Manager
Space Systems Division

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